Preparing for Earthquakes in Dallas-Fort Worth:
Applying HAZUS and Network Analysis to Assess Shelter Accessibility

by

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List of Abbreviations

CEUS: Central and Eastern United States

CDMS: Comprehensive Data Management System

DFW: Dallas-Fort Worth

FEMA: Federal Emergency Management Agency

HAZUS-MG: Hazards United States Multi-Hazards

NEHRP: National Earthquake Hazards Reduction Program

NTCOG: North Texas Council of Governments

OKC: Oklahoma City

PESH: Potential Earthquake Science Hazard

USGS: United States Geological Survey

WUS: Western United States

Abstract

Earthquakes, which were previously rare events in the Dallas-Fort Worth (DFW) Metroplex, have become increasingly common in the last five years. In a five-month period, Irving alone had 26 earthquakes over magnitude 2.0. Damage has been minimal, but larger earthquakes have not been ruled out as new fault lines have been discovered and their precise structure is only beginning to be understood. This project's goal was to show how HAZUS can be used to demonstrate possible earthquake effects on the new fault lines, and how the results from HAZUS can be used to assess the impact of damaged bridges on the road network and shelter accessibility. Two fault lines discovered in the last couple of years were digitized and loaded into the HAZUS model. Historical earthquake data were used to form a hypothetical earthquake scenario that characterizes local conditions. The scenario was run twice, once on each fault.

To explore how these results can inform emergency planning, output from the HAZUS scenarios regarding the amount of people needing shelter per census tract, as well as damage to bridges and their location, was imported into ArcMap. A road network was built to support a location-allocation model to assign people needing shelter to potential shelters and the damaged bridges were added as barriers. A centroid was calculated for each census tract to provide population source points. Lacking data on the location of existing emergency shelters, all schools throughout the two counties were designated as potential shelter destinations. Then location-allocation analysis was conducted on each county’s data to determine the closest accessible shelters with available capacity. The demonstration scenario resulted in not enough shelters, as several source points were unallocated. It is hoped that the demonstrations provided by this study will encourage city planners to begin to address emergency planning in the region for these newly identified hazards.

Chapter 1 Introduction

Several cities in the Dallas-Fort Worth (DFW) Metroplex, a historically quiet area geologically, have suffered multiple, frequent earthquakes whose cause has been linked to wastewater injection wells that accompany fracking for natural gas (Hornsbach et al. 2015). Cities and counties in the Metroplex area have shown little consideration for earthquake-related issues, with the Texas state hazard plan labeling an earthquake event as unlikely (Texas Department of Public Safety 2015). This thesis demonstrates how HAZUS can be used to evaluate possible damage from an earthquake, and how the results from that analysis can be used to plan for the now likely earthquakes.

The DFW Metroplex encompasses 12 counties in North Texas, but the core with the highest population are Dallas, Tarrant, Denton, and Collin counties. DFW has a population of 5.92 million, with Tarrant and Dallas having the highest population densities. The area is also one of the fastest growing in the nation (Young 2015). These core counties sit on unique geologic structures that are now known to make an earthquake possible in what should be a geologically quiet area (Jordan 1977).

Because the DFW Metroplex sits on the eastern edge of the Barnett Shale, a hydrocarbon rich formation, many new wells have been dug to extract oil and gas since fracking makes previously impossible extractions much more profitable (Galbraith 2013). Fracking is the process of injecting high pressure water, sand and chemicals into the well to allow gas to pour out (BBC 2013). The waste water and chemicals coming out of these wells are subsequently disposed of in injection wells. Recent concern comes from the increase in earthquakes attributed to injection wells being positioned near previously undetected fault lines and the injected liquid resulting in fault slippage. Previous studies have pointed to wastewater injection wells as a possible cause of these earthquakes (Hornsbach et al. 2015)

The goal of this project was to demonstrate how HAZUS and ArcMap can be used to assist in disaster planning for this new hazard in the DFW area. This was accomplished by showing how accessible shelters for displaced residents can be identified using a road network that incorporated damaged bridges predicted by HAZUS modeling. The 5.5 magnitude for the modeled earthquake scenario was determined by recent statements from researchers who cautioned that an earthquake stronger than the recent uptick in 2 to 4 magnitude earthquakes cannot be ruled out (Stump 2015).

1.1 Motivation

From October 2014 to March 2015, the city of Irving in Dallas County recorded over 20 earthquakes. While the majority were under magnitude 3.0, six were between 3.0 and 3.6 (Earthquake Hazards Program 2016), which can cause slight damage close to the epicenter. These stimulated discussions on earthquake frequency, and potential future consequences within the community (Selk 2015). Researchers at Southern Methodist University (SMU) are doing research into these local earthquakes, and their conclusions have linked the earthquakes to new faults that are potentially affected by nearby oil wells (Frolich et al. 2010). Their statement that stronger future earthquakes cannot be ruled out is the motivation for this project.

Responding to this concern, this research explored the potential damage that might occur to bridges from such larger earthquakes, the amount of people affected that will need short term shelter, and whether this damage would affect their ability to get to shelter locations. This analysis used the HAZUS (HAZards United States) model which was created by FEMA (Federal Emergency Management Agency) to help localities prepare for hazards in the future and plan ways by which to mitigate losses. In such an earthquake scenario, it is critical that the shelters be accessible by road, which was examined by using the Network Analyst toolset in ArcMap. By using these tools, it addresses the main questions of this project: Following a 5.5 earthquake along these newly discovered faults, how many people may need shelter due to damaged homes and might there be an impact on the road network caused by damage to bridges that will make shelters inaccessible? Practically, can ArcMap be used to model access to shelters using damage results from HAZUS?

HAZUS-MH 2.2 has been used in Texas for analyzing damage from flooding and hurricanes, however, earthquakes have traditionally been very rare and of small magnitude, which makes planning for a moderate sized quake a low priority. Tarrant County does not list earthquakes as a hazard in their hazard planning guide (Tarrant County 2015), and Texas's statewide emergency planning guide only casually mentions earthquakes (Texas Department of Public Safety 2013). The most likely threat according to Texas's planning guide comes from the New Madrid fault, which lies at the border of Missouri, Kentucky, Arkansas and Tennessee. The Texas guide does suggest that if earthquakes persist, local planners would benefit from adjusting building codes to increase structural stability. This study demonstrates this gap in hazard analysis by demonstrating a methodology that can be used to analyze in advance potential damage to crucial road networks and to show how this damage might affect the ability of people in the surrounding areas to travel to shelters.

1.2 Goal of this research

This project's goal is to help encourage disaster planning in Texas based on the recent occurrences of earthquakes. Shelters are crucial if people's homes are too damaged to live in, so this project sought to demonstrate how accessible shelters can be identified using a road network that incorporated bridges too damaged for travel.

1.3 Outline of this document

This document next moves into Chapter 2 to a review of the background research that guided its development, which is important since Texas has experienced few earthquakes and guidance must be found elsewhere. Chapter 3 describes the research method that was split into several parts: analyzing historical earthquake data; creating and loading faults; applying the HAZUS model; and using network analysis to address shelter needs. Chapter 4 explains the results from running HAZUS and the location-allocation tool. From this, conclusions were drawn and these are discussed, along with suggestions for future research and policy development in DFW in the final chapter.

Chapter 2 Background

In order to understand the reason for the project, it is important to understand the Texas earthquake context and several related concepts. The geology of the state is the fundamental base that makes earthquakes possible. The history of these earthquakes is important to document to address potential impact in the study area. HAZUS was a key program used in this project, and its usefulness is detailed through several studies as a guide to how it should be used. Studies for locating emergency shelters using location-allocation are discussed as a guide to constructing the methodology.

2.1 Study Area

The Dallas-Fort Worth Metroplex refers to a group of 12 counties in North Central Texas. The study area for this project covers Dallas and Tarrant counties, which houses 71 towns and cities, as shown in Figure 1. The Metroplex is home to 5.92 million inhabitants and is one of the four largest metro areas in the United States. It was second nationwide in growth rate between 2013 and 2014 (Young 2015). With continued growth comes concern about the increase in the level of damage from natural hazards. This is especially important since Dallas County houses a fault near Irving, and Tarrant County has a fault near Azle.

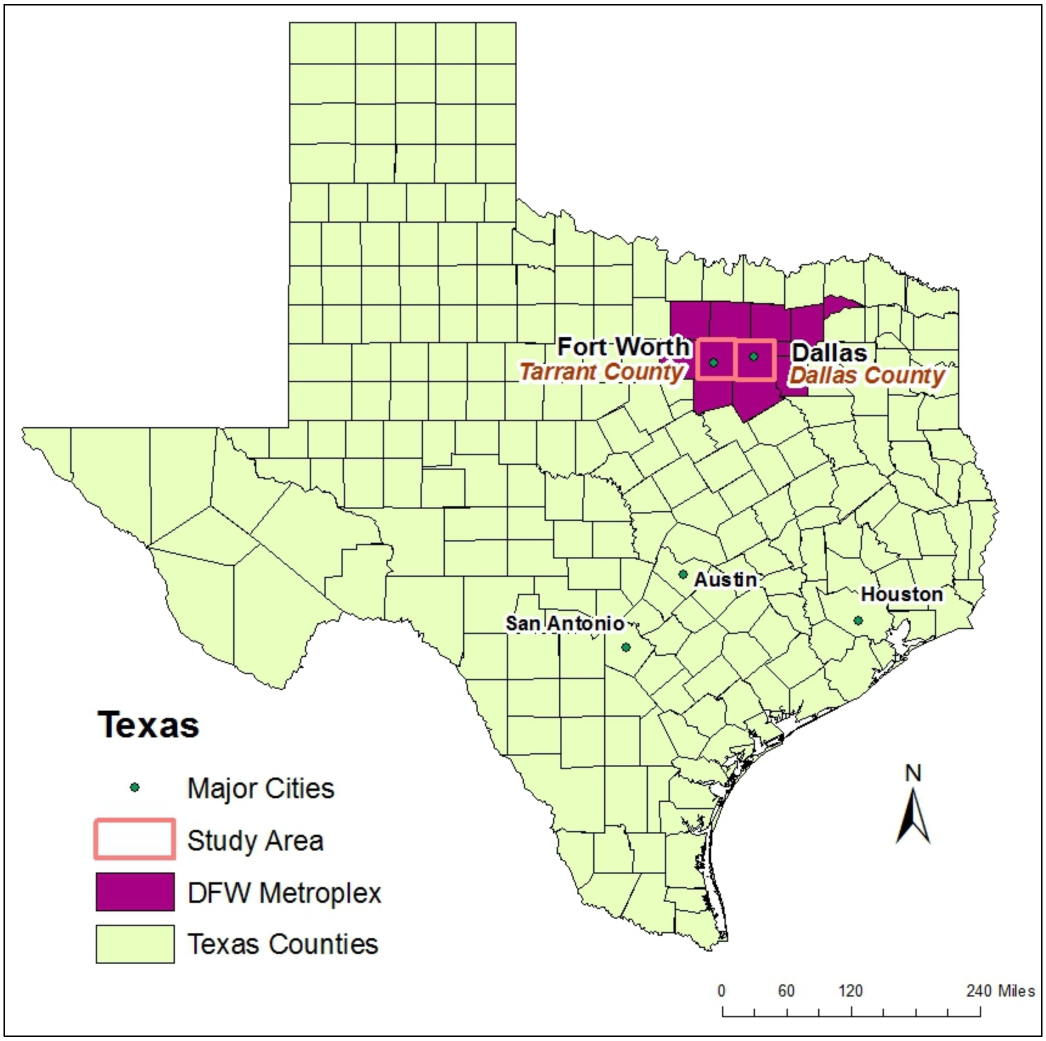

Figure 1 Study Area

2.2 North Texas Geology

What makes earthquakes in Texas possible, despite millions of years of inactivity, is the unique geology of the state. The Balcones Fault Zone runs from southwest Texas near Del Rio to the northwest, close to Dallas (Figure 2). It is a collection of many smaller faults and was the result of strain during the Tertiary era approximately 66 million years ago (Jordan 1977). The faulting ended in the Miocene epoch between 23 and 5 million years ago, with relatively little activity since.

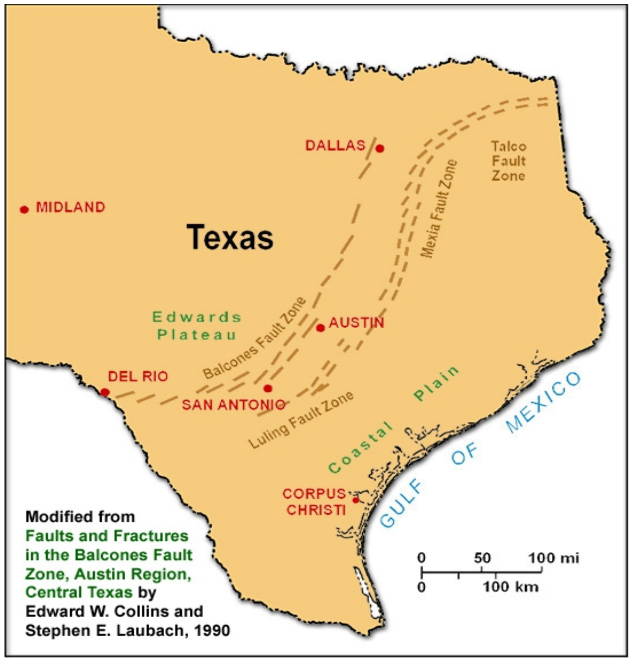

Figure 2 Balcones Fault Zone (Source: University of Texas 2016)

The other major geological feature in the study area is the Barnett Shale. It is a large natural gas producing formation that encompasses 18 counties (Figure 3). It is normally associated with the Fort Worth Basin. It provides a large economic incentive to drill the area, with royalties, taxes and fees providing a great boon to cities and their residents. Fracking and horizontal drilling made efficient drilling possible starting in 2002.

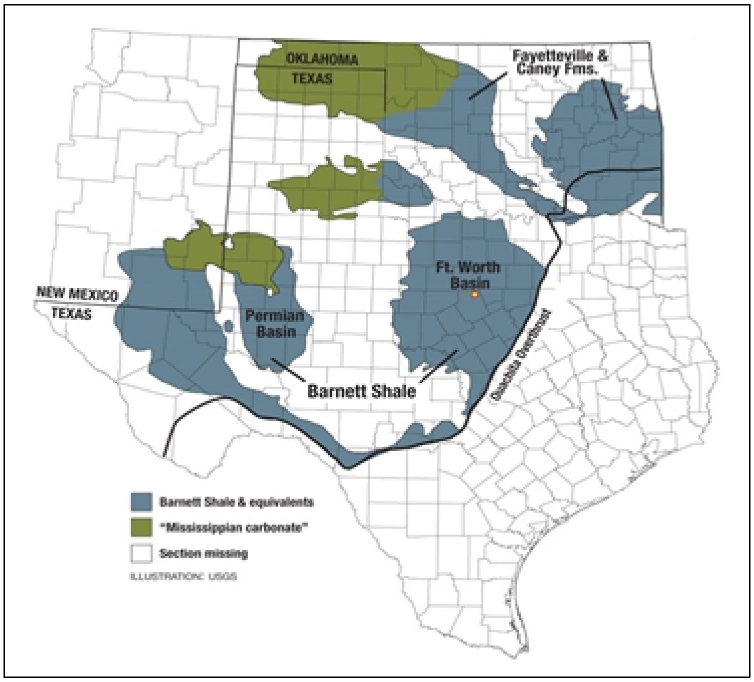

Figure 3 Barnett Shale / Fort Worth Basin (Source: University of Texas 2007)

2.3 Earthquakes in Texas

Researchers at Southern Methodist University (SMU) in Dallas have been recording and analyzing these North Texas earthquakes since they became a prominent concern in 2009. Their goal was to determine what the cause was in order to better address the issue going forward. An initial study first looked at how they could determine earthquake location and explored a correlation between oil exploration and earthquakes (Frohlich et al. 2010). They measured P and S wave arrival times, as well as the locations of several wells and the amount of brine injection per day.

After a series of quakes in 2013 near Azle, the group of SMU researchers looked more in depth to the causes. They located an ancient buried fault line (Figure 4), and then measured both natural stress changes from water table changes and tectonic stress. This was then compared to stress changes due to the oil and gas industry's extraction and injection methods. They concluded that the human-induced activity produced the most significant stress changes (Hornbach et al. 2015). However, why some areas with wells have earthquakes and others do not was reported as unclear.

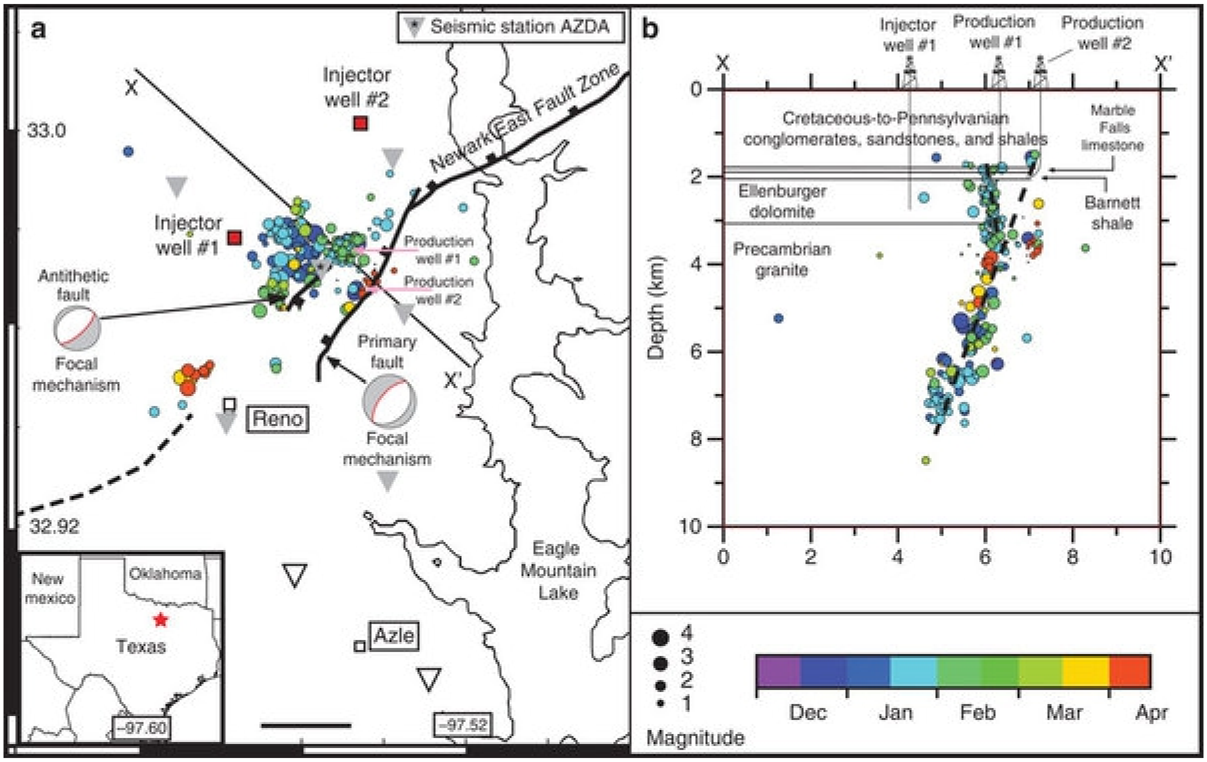

Figure 4 Azle faults and earthquakes. The fault used in this project is the Antithetic fault identified on the center left side of the map. (Source: Hornbach 2015)

In 2016, the USGS released a report by Peterson and other researchers detailing earthquake hazard areas that included human-induced earthquakes for the first time. It focused on large areas of Oklahoma, but also included the DFW area. Their study used five different parts of the seismic model created for their report to evaluate risk, which includes earthquake maximum magnitudes and earthquake locations (Petersen et al. 2015). The report details hazard risk over the course of a year instead of 50 years, as policies that can affect induced earthquakes can vary year to year. In a summary of the report, the USGS added that while human-induced earthquakes may have lower magnitude than natural earthquakes, induced quakes may trigger larger quakes (Fitzpatrick and Petersen 2016).

2.2 HAZUS

The HAZUS model was created by FEMA in 1997 to estimate potential losses from earthquakes, floods, and hurricanes. This was to help local officials plan for the after effects of disasters and mitigate the losses. HAZUS is a large complex model framework composed of many different modules that simulate the impact of hurricane, flood, and earthquake scenarios on a study area created by the user. It and the state datasets are free to download from FEMA's Flood Map Service Center HAZUS page. It incorporates ArcGIS to visualize the impacts of a hazard on any given category, such as hospitals or utility systems. It also can estimate the amount of casualties that a population may suffer, as well as how many may need shelter. It has three different levels of usage, with level 1 using only default data, and level 3 being heavily customized with local knowledge. As noted above, in Texas, the most used applications of HAZUS are for understanding the impacts of flooding and hurricanes, with earthquakes not yet being seen as a large issue.

HAZUS uses ArcMap as a means by which to map results and to add data such as custom fault lines from outside the model itself. It comes with an extensive database inventory that includes details about residential, commercial, and industrial buildings, as well as transportation networks and schools. This inventory can be expanded by the user by importing their own data. Damage is measured as direct damage to structures, and direct and indirect social and economic losses.

The HAZUS earthquake module uses the Physical Earth Science Hazard (PESH) model to measure ground motion and ground failure. There are 59 equations available to determine ground failure, including the Atkinson and Boore equation that is used in one of the studies discussed below. The actual equations used in a particular model run are filtered based on the study area created and can be chosen by the user. Ground motion is determined by attenuation models for Western United States (WUS) and by ground-motion prediction equations for Central and Eastern United States (CEUS), as well as spectral contour and probabilistic hazard maps by the USGS. Scenarios are either pre-made or custom set by the user

2.2.1. HAZUS for earthquakes studies

In 2008, FEMA determined the average Annual Earthquake Loss (AEL) and average Annual Earthquake Loss Ratio (AELR) risks for all states. Texas fell in the bottom half of both measurements (FEMA 2008). While the FEMA study showed the AEL is moderate for this project's study area with an AEL rating of 1 to 5 million dollars, the higher rating is because of the large population and abundance of structures involved. Figure 5, which was drawn straight from the FEMA study, shows the AEL for the United States. Tarrant County used HAZUS in their latest hazard mitigation action plan, but did not include earthquakes (Tarrant County 2015), as to date most earthquakes have been minor to light.

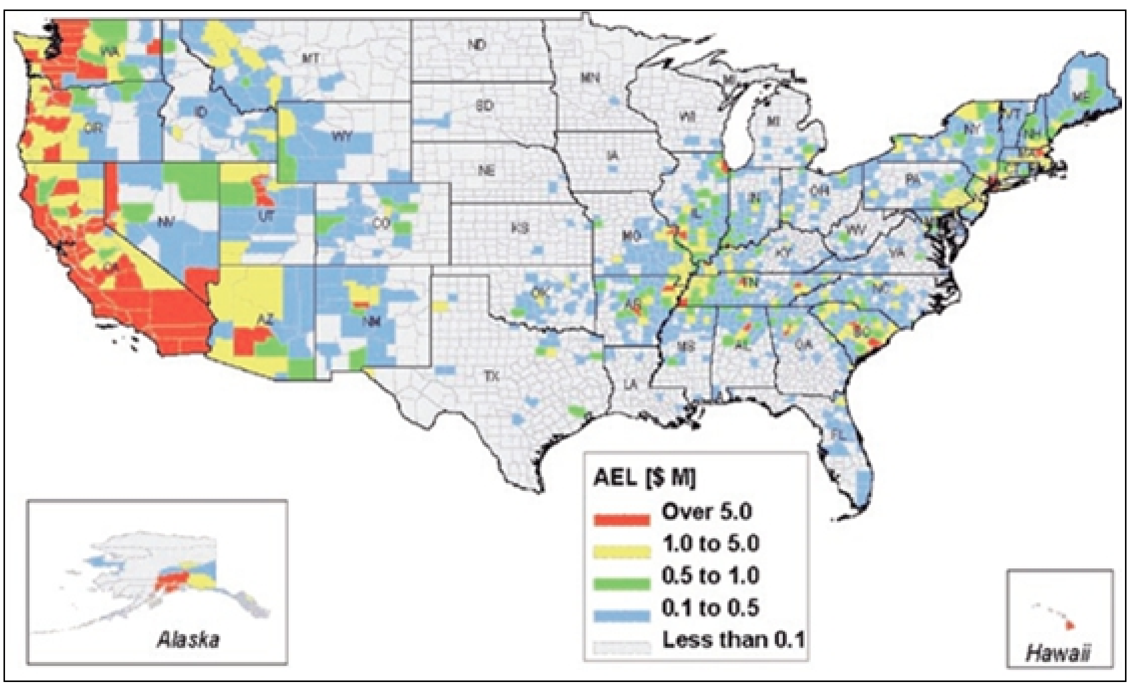

Figure 5 Annual Earthquake Loss (Source: FEMA 2008)

To see how HAZUS has been used to understand earthquake damages, it is necessary to look at areas with a high potential of earthquakes. Ploeger (Ploeger, Atkinson and Samson 2010) studied earthquake potential in Ottawa since it is the capital of Canada, has nearby fault lines, and a history of moderate historical earthquakes. Ploeger's study uses the Atkinson and Boore equation in HAZUS to determine ground shaking for the earthquake model as it provides amplitude as a part of the earthquake distance and magnitude measurements. This predication was compared to expected ground motions included in the 2005 National Building Code of Canada. The study also included soil classes as key input as soils can amplify movement. The soil classification system used is from the National Earthquake Hazard Reduction Program (NEHRP), and they used the SITEAMP program to convert velocity and density into amplification. Data preparation was extensive, but HAZUS is not as complete for Canada as it is for the US so Ottawa buildings were classified by visual inspection. In an earlier study by the same author (Ploeger et al. 2008), they got around the lack of Canadian ground motion and geographic conditions by using New York settings and replacing all the building data with Ottawa data. PESH, which needs soil classification, liquefaction and landslide susceptibility, and water depth data, was a guideline used by the author to collect the necessary Ottawa data.

The USGS applied HAZUS to King County in Washington due to the numerous faults, distance to edge of a tectonic plate, and susceptibility to large earthquakes. They also emphasized ground motion through use of the PESH model (Neighbors et al. 2013). They created seven scenarios to compare and contrast results, split between shallow and deep earthquakes. They used three sources of input: one from HAZUS historic catalog and two from the researcher's own input. Each of these were run in both HAZUS default hazard input mode and user input mode influenced by NEHRP. Variation in ground motion was compared to economic building damage. They noted higher values in peak ground acceleration and economic building damage compared to using user-sourced input. This was credited to inaccurate flaws in the default settings for earthquakes in HAZUS and the authors commented that it is important to use information from previous studies and local data instead. By using user supplied data, the values for damage and ground motion magnitude were reduced.

2.3 Locating Emergency Shelters

Emergency planning is a crucial function of municipalities, and identifying locations that can be used as shelters is a key part of that process. Schools, community or recreation centers, and churches are the most commonly identified shelters in Texas (TXDPS 2015). Also, as seen in New Orleans following the Katrina hurricane, indoor sports arenas can also house people temporarily. Private entities such as the Salvation Army can also provide shelter if the people come from an emergency shelter and/or can be regarded as homeless, according to their regulations (Salvation Army 2016). GIS has played an important role, using location-allocation and other models, to determine if there are shelters in places where they are needed.

2.3.1. Using GIS to identify shelter locations

Kar and Hodgeson (2008) used GIS with a Weighted Linear Combination (WLC) model and combined it with a Pass/Fail technique to identify which shelters were in suitable and non-suitable areas. Values for the factors were determined by a rule-based technique that included criteria such as proximity to highway and not being within 10 miles of a nuclear power plant. Weights were determined by an opinion-based technique. The final value was determined as weight multiplied by factor value. Excluded variables had a factor value of 0. This was then mapped in raster format due to the large number of facilities and the large study area of Southern Florida.

2.4 Location-Allocation

Location-allocation chooses the best site(s) based on pre-determined criteria, such as travel time, for the surrounding population situated at demand points. It does this by allocating the demand points to the best fit facility(s) (Esri 2016). Such models requires a road network built from facility and road data, and identification of any impedances to road travel. In any implementation of location-allocation, there are several options for the Problem Type setting but Minimize Impedance and Maximize Coverage are the best for planning public services such as shelters (Polo et al. 2016). To run the tool, the facility destination points, the demand points, the road network, and any properties essential to the specific project must be provided. The result is a map of both candidate and chosen facilities, with lines showing which demands points are allocated to each facility.

2.4.1. Location-allocation for emergency shelter planning

Previous studies have applied location-allocation specifically to exploring emergency shelter locations. Wu and others focused on applying this technique to the Yushu Tibetan prefecture in China in order to help human life, property, and guide the government's planning to protecting its citizens (Wu et al . 2015). The authors extracted alternative shelters from a digitized map, identified and drew important features such as first aid centers and water sources, and created the road network from scratch by shaping and drawing the roads. The authors also established an index system that prioritized safety, accessibility, and if it is fit for use. After building the network, the authors determined the weight for each index using an analytic hierarchy process. They used arithmetic average as the optimization strategy of the model, and natural breakpoint to divide the level. Anything above .5 was determined to be the best location, and below .3 was not recommended to be a shelter location.

Kongsomsaksakul, Yang and Chen (2005) used location-allocation for locating shelters, focusing on the implementation of the technique rather than on a specific practical application. He used bi-level programming, with the assumption that the city administrators would designate shelters, while the citizens would choose from those shelters. He used multiple mathematical formulas, the city of Logan's road network in Utah as a case study, and 10 pre-defined shelter locations. As would be expected, shelter capacity had a large effect on the travel time, with smaller capacities increasing the time it took by redirecting to the next closest shelter with capacity. He also looked at the impact of shelter location on travel time, showing that the removal of two shelters increased the travel time by several minutes. Combining both Kongsomsaksakul and Kar's studies, while out of date with current GIS technology, gives guidance on shelter choice and road network impact for the location-allocation model in this project.

2.5 Summary

The importance and motivation for this project is fueled by the geologic and demographic context of the state of Texas. The populous DFW area sits on the Balcones Fault, which is an essential concern as it houses many fault lines. Earthquakes have been rare until 2009, and this recent increase is thought to be connected to wastewater injection wells. HAZUS can simulate the effects of earthquakes in order to visualize the possible effects on an area, which allows for the study of a specific scenario to occur in the DFW area. Previous studies provided guidance on how to execute HAZUS accurately. The results from HAZUS can be incorporated into ArcMap to assist in planning how to handle a population with no home to return to. To this end, location-allocation is useful as it locates the best facilities for the demand points to travel to given particular objectives such as minimum travel time. Previous studies provided detail on how it should be done and how shelters should be allocated. In the next chapter, how these methodologies were applied to an examination of the earthquake hazards in the study area is described.

Chapter 3 Data and Methodology

This chapter begins with a description of the data used. Then, the methodology is discussed in two parts: using HAZUS and using ArcMap. HAZUS was run using a single scenario on two different faults, Irving and Azle. Bridge damage and shelter needs results from HAZUS along with potential shelter locations and road data were then incorporated into ArcMap in order to build a road network with the damaged bridges as barriers. From this, location-allocation was run in order to determine the closest shelters to meet the needs of the newly homeless in each census tract.

3.1 Data Used

Most of the data needed for this research was readily available, thanks to the federal government. As noted above, HAZUS comes preloaded with a large data inventory, which is expansive for the study area since it has a high population. The inventory can be further customized with local knowledge if needed. The USGS offers earthquake point data for free through their Earthquake Hazards Program, which can quickly be loaded into ArcMap.

The fault lines proved to be the trickiest data to create. Hornbach et al. (2015) published the locations of the faults, although only in descriptive format. USGS does provide fault line data, but neither the Azle nor Irving fault lines were included. The Irving fault line was only discovered in February 2015, and while Azle was known prior to that, the study noting its location came out in 2015. Thus as HAZUS does not include these fault lines, multiple steps, described below, were required in order to use them in in this research.

School locations, bridge locations and damage estimates, and shelter needs, data necessary for the Location-Allocation component, were obtained from the Results tab in HAZUS. These results can be exported as shapefiles and loaded into ArcMap for manipulation and analysis. The location of potential non-school shelters, such as recreation centers and sports arenas, were obtained through city and county websites which list recreation centers and nearby sports centers. The only sports centers that were included were fully enclosed buildings such as the AT&T Stadium in Arlington.

Road data was acquired from the North Texas Council of Government's (NTCOG) website. It was split into two shapefiles: streets and highways. Lakes were included as background data because Eagle Mountain Lake serves as a barrier to population growth to the east of the Azle fault. It also limits travel as only a few bridges cross it. More on each of these data sets is provided in the following sections.

3.1.1. HAZUS census tract base data

HAZUS uses census tracts as the base polygon layer to identify at risk areas and to compile damage statistics. The population and population density per square mile for 2010 for each census tract are included in the inventory data. Figure 6 shows population density for the two counties in the study area. These were classified using the natural breaks method as there were breaks in the data, with Dallas having noticeable break points at 10000 and 25000 while Tarrant increased a lot after 7000. In addition, Dallas was classified into six classes because there were two census tracts with abnormally high densities, compared to the rest of the county, and should be their own class. All inventory data and their specific characteristics are associated with a census tract, although essential facilities also have addresses and names which allow for point data creation. Residential and commercial buildings only have codes that identify building type. This allows HAZUS to calculate the effect of a scenario per each census tract, creating a targeted analysis and view of the study area.

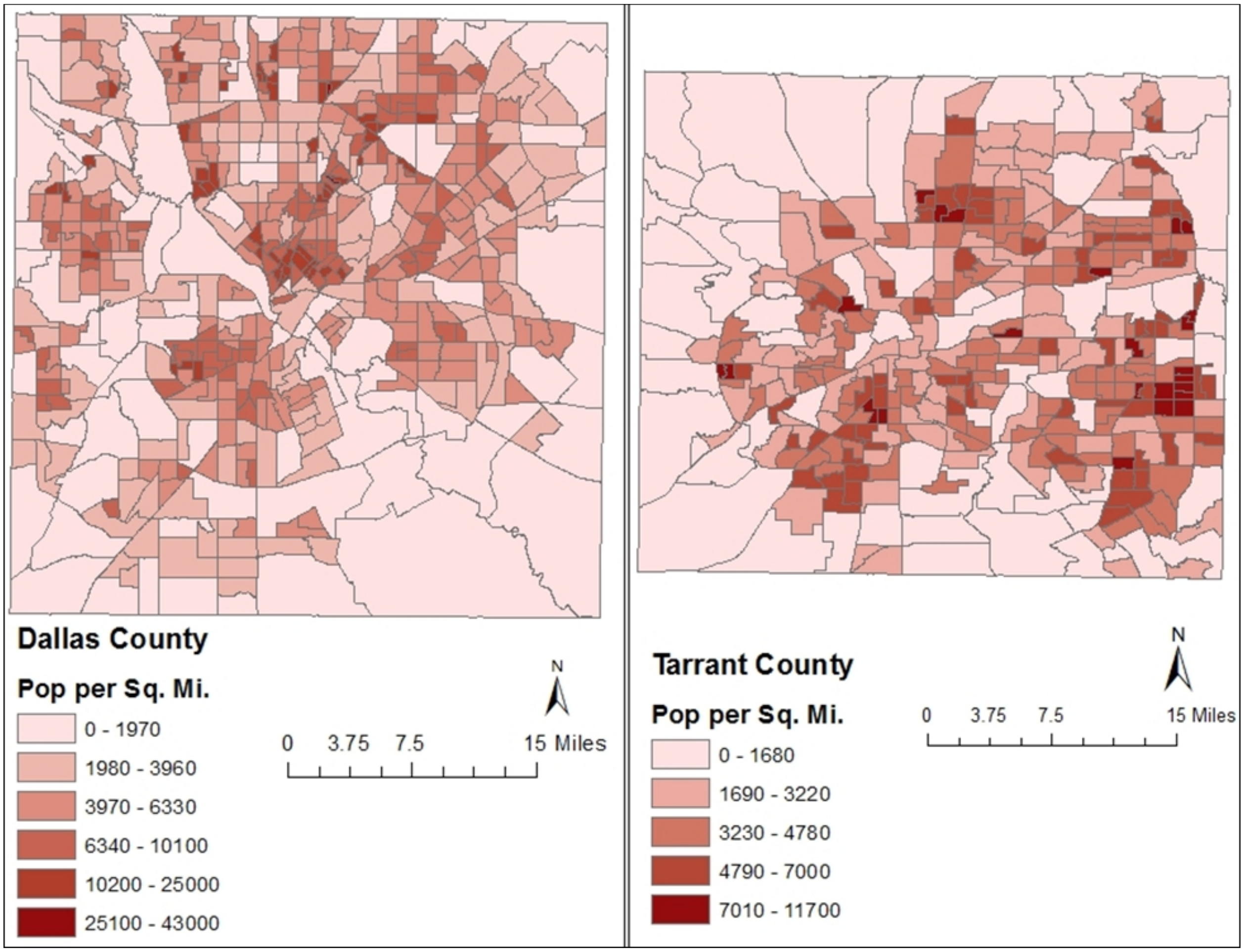

Figure 6 Population Density for Dallas and Tarrant County

3.1.2. HAZUS inventory data

Building type, construction materials, height, occupancy type, and address are just some of the many building attributes that must be present in the inventory for HAZUS to conduct an accurate analysis. HAZUS comes with an extensive list of structures in its default database, with user defined buildings incorporated as General Building Stock (FEMA 2015). Some of these structures are stored in the aggregate by census tract, others are stored individually. Although residential housing is critical when calculating the damage estimates and determining how would many people need shelter if their homes are too damaged, residences are only identified by code, depending on building type and construction, and cannot be mapped individually as they do not have an address. Instead, each building is associated with a census tract, with results showing damage per building category per census tract.

On the other hand, critical facilities such as schools and hospitals are stored individually. Table 1 shows a sample of Essential Facilities, which is one of many categories of inventory. Each building has a class designation, where the definition of each is preset by FEMA as seen in Table 2. All classification codes are listed in the data dictionary from FEMA. For HAZUS to calculate various effects on the study area, each piece of inventory data must be associated with a census tract.

Table 1 A Sample of Individual Structures in a HAZUS Essential Facilities Category

ID Number	Class	Tract	Name
TX000004	EFHL	48113014601	Baylor Medical CTR at Irving
TX000026	EFHM	48113006301	Dallas Southwest Medical Center
TX000031	EFHM	48113019211	Baylor/Richardson Med Center
TX000045	EFHL	48113008100	Doctors Hospital of Dallas
TX000062	EFHS	48113010000	Mental Health Connections
TX000063	EFHL	48113000401	Parkland Health & Hospital

Table 2 HAZUS Facility Classification Definitions

Class	Description
EFClass	EFHL = Large hospital EFHM = Medium hospital EFHS = Small hospital EFMC = Medical clinic

Bridge locations and schools were able to be plotted directly into ArcMap, but the residential data could only be aggregated at the census tract level. Bridge damage and shelter need attributes can be associated with the bridges and census tracts, respectively, after a scenario is run. Bridge data can also be acquired by running a scenario and selecting transportation results. Shelter needs can be mapped per census tract, and are summarized in a table.

3.1.3. Fault Lines

Fault lines are typically where earthquakes happen, as they are the result of slippage and releasing of pressure. While the USGS makes these available, the Azle and Irving faults have not been loaded into HAZUS as they were only discovered in 2013 and 2015, respectively. Both of these are also sub-surface faults, which makes precise locations difficult to measure. Seismometers and tracking of earthquake epicenters are used to determine the approximate location, but the margin of error for Irving is approximately half a mile due to it still being poorly understood (Deshon et al. 2015). It is described as “a narrow two-mile line which indicates a fault extending from Irving into West Dallas, running north-by-northeast from TX Highway 114 to Walnut Hill Road along the Trinity River” (NBCDFW 2015, p. 1) in Dallas County. The Azle fault in Tarrant County is better mapped, as seen above in Figure 4. Lines representing these faults were built in ArcMap from the available maps and descriptions using the edit tool to create shapefiles (Figure 7). Their precise location is not critical in this study.

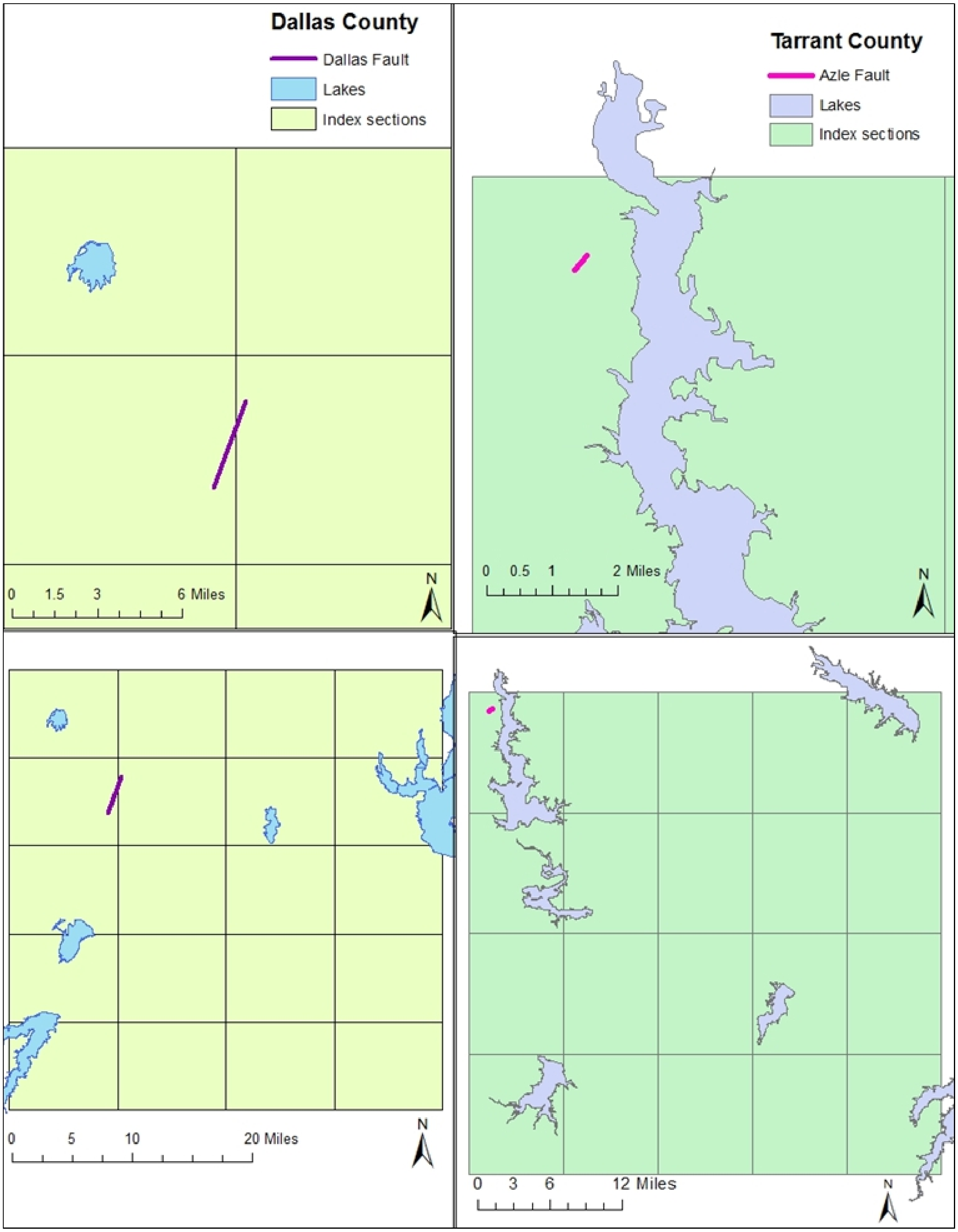

Figure 7 Azle and Irvine faults as mapped for this project. Bottom images show the entire counties.

3.1.4. Historic earthquakes

It is important to know the attributes of historical earthquakes in the area in order to create a scenario that represents local conditions. Epicenter location, depth, and magnitude are all important factors for an accurate scenario. The earthquake data for earthquakes is made public by the USGS and can be downloaded in CSV format, with location given as latitude and longitude coordinates in WGS 1984 datum. The data for earthquakes that occurred in the area post-2009 were downloaded, imported into ArcMap and converted into a point shapefile ().

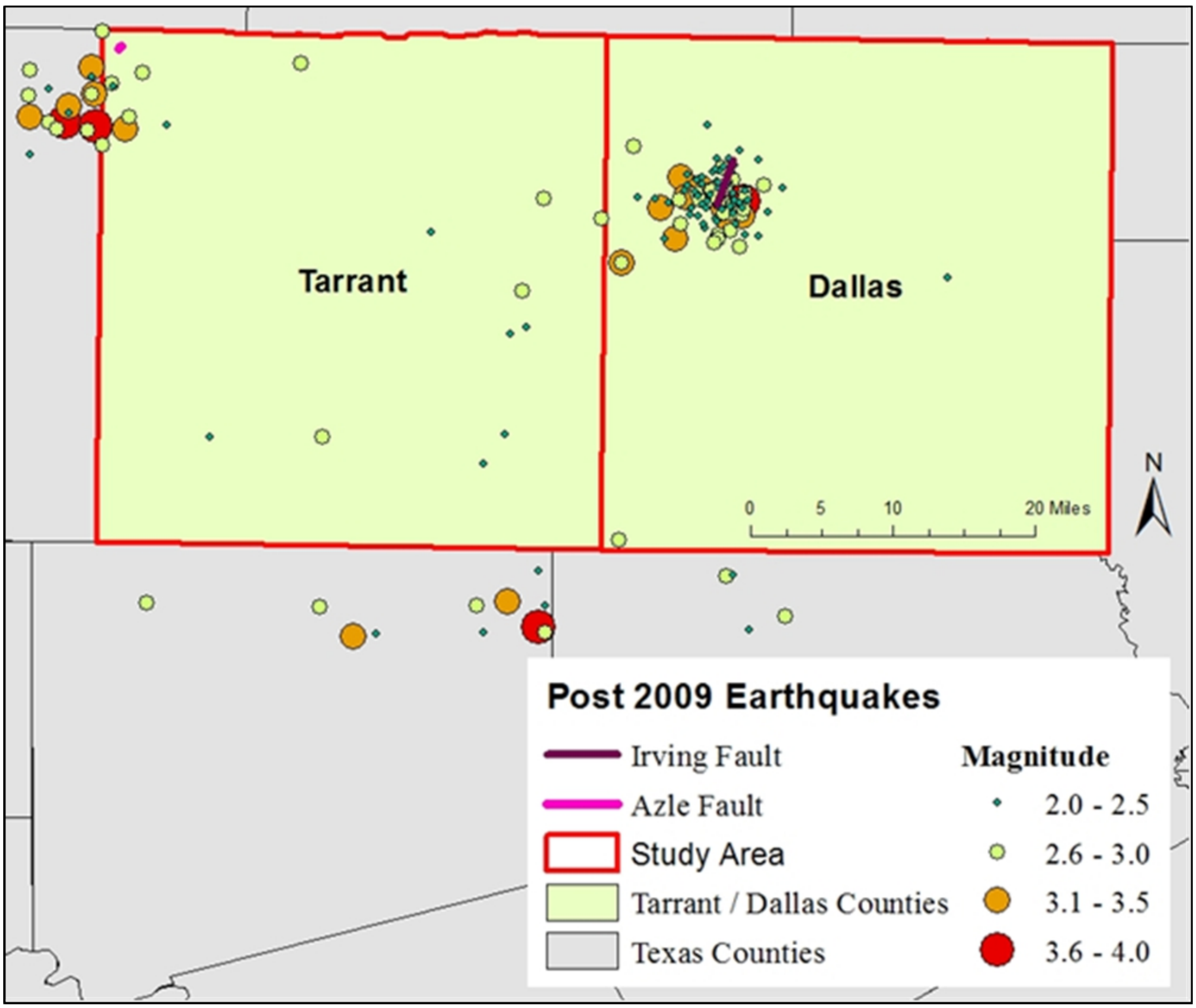

Figure 8 Post-2009 earthquakes in the study area

In order to run HAZUS, an earthquake scenario must be created that specifies the horizontal epicenter, magnitude and depth. Using statements from Heather Deshon et al. (2015) from SMU as justification, a 5.5 magnitude event was used. Depth for the scenario was determined by averaging the depths of all the earthquakes recorded by the USGS in Tarrant and Dallas counties post-2009. Epicenters for the earthquakes for the scenarios were located directly on the Azle and Irving fault lines. Both Azle and Irving are short faults of two miles or less and their locations are not accurately known, so an imprecise determination of the location of the scenario epicenters is sufficiently representative of potential earthquakes in the area.

3.1.5. Roads

In order to create a location-allocation model, a topological road network is required. Roads and highway line data were downloaded from the North Texas Council of Government (NTCOG) website. Using the network construction tool in ArcMap, these line segments were converted into a fully connected network dataset. Based on local knowledge of the area, speed was assigned as 40 miles per hour for segments classified as roads and 70 miles per hour for highways. This information was used by the location-allocation model to calculate the time it would take to travel each segment and ultimately to determine the closest shelters to each census tract.

3.1.6. Shelters

Shelters are any building that is designated by either state or local municipalities to house people temporarily. For this project, it is where people can go after their homes are damaged or destroyed by an earthquake. Schools are a common type of shelter, and their location can be directly downloaded from the HAZUS inventory as point data. There were approximately 2700 schools within Tarrant and Dallas counties, and several hundred additional were included from the bordering counties to see if they would be closer to travel to for the border census tracts.

Recreation centers and indoor sports arenas were also included as shelters in the analysis, although they were not present in the default HAZUS data. Therefore, it was necessary to retrieve the names and addresses of such facilities from the city websites, recording each facility listed in a spreadsheet. Salvation Army and sports arena addresses were also acquired through their websites. All of these were then geocoded using their addresses, and a point shapefile was created. This was done for each county. Error: Reference source not found shows the distribution of all shelter points compiled.

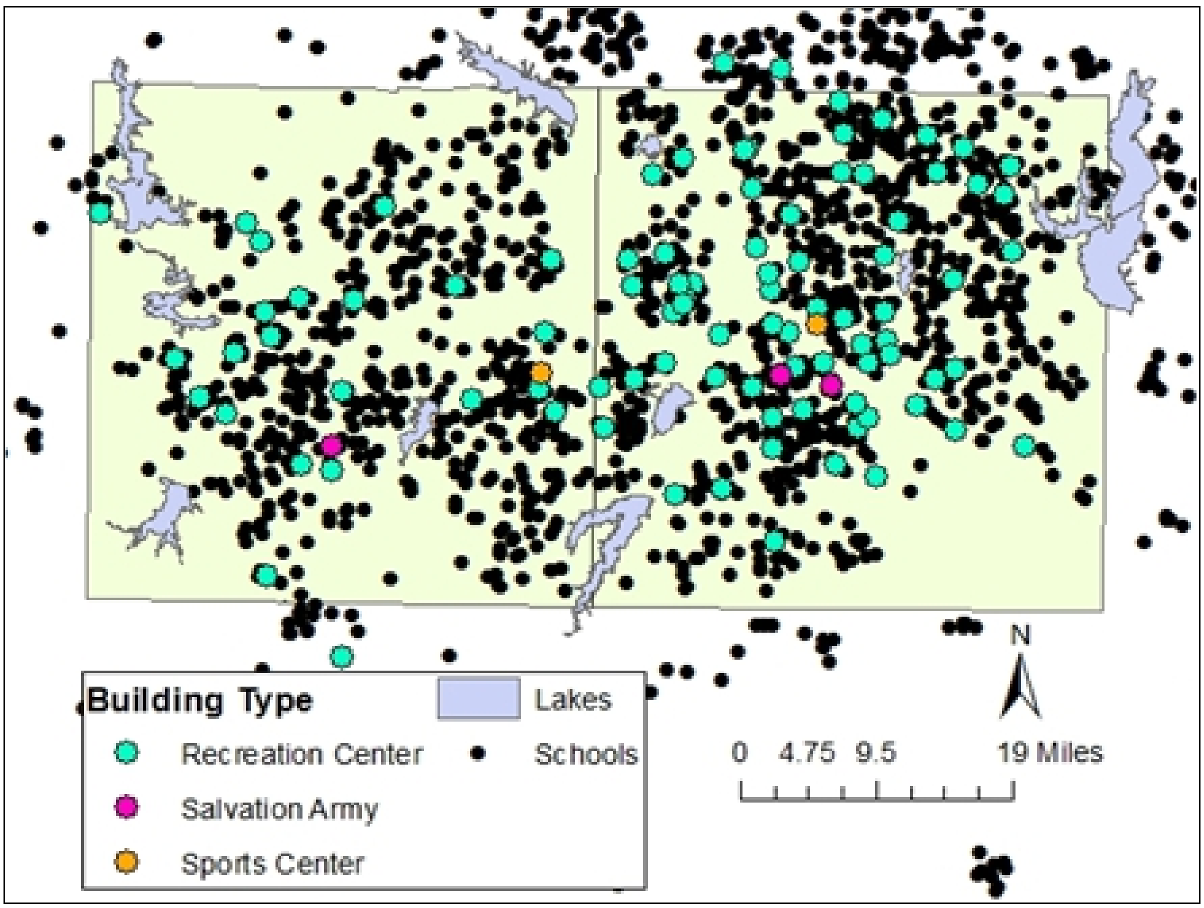

Figure 9 Potential shelter locations, including schools, recreation centers, Salvation Army shelters and sports centers

3.2 Methodology

The methodology has two parts: hazard modeling using HAZUS and network analysis using ArcMap. HAZUS results provided input for the ArcMap analysis step. HAZUS used earthquake data to predict damage from a hypothetical earthquake scenario, in particular which bridges would be too damaged for travel, and how many people would need shelter after an earthquake event. These results were then exported into ArcMap where a transportation network was built and a location-allocation analysis performed. outlines the methodology.

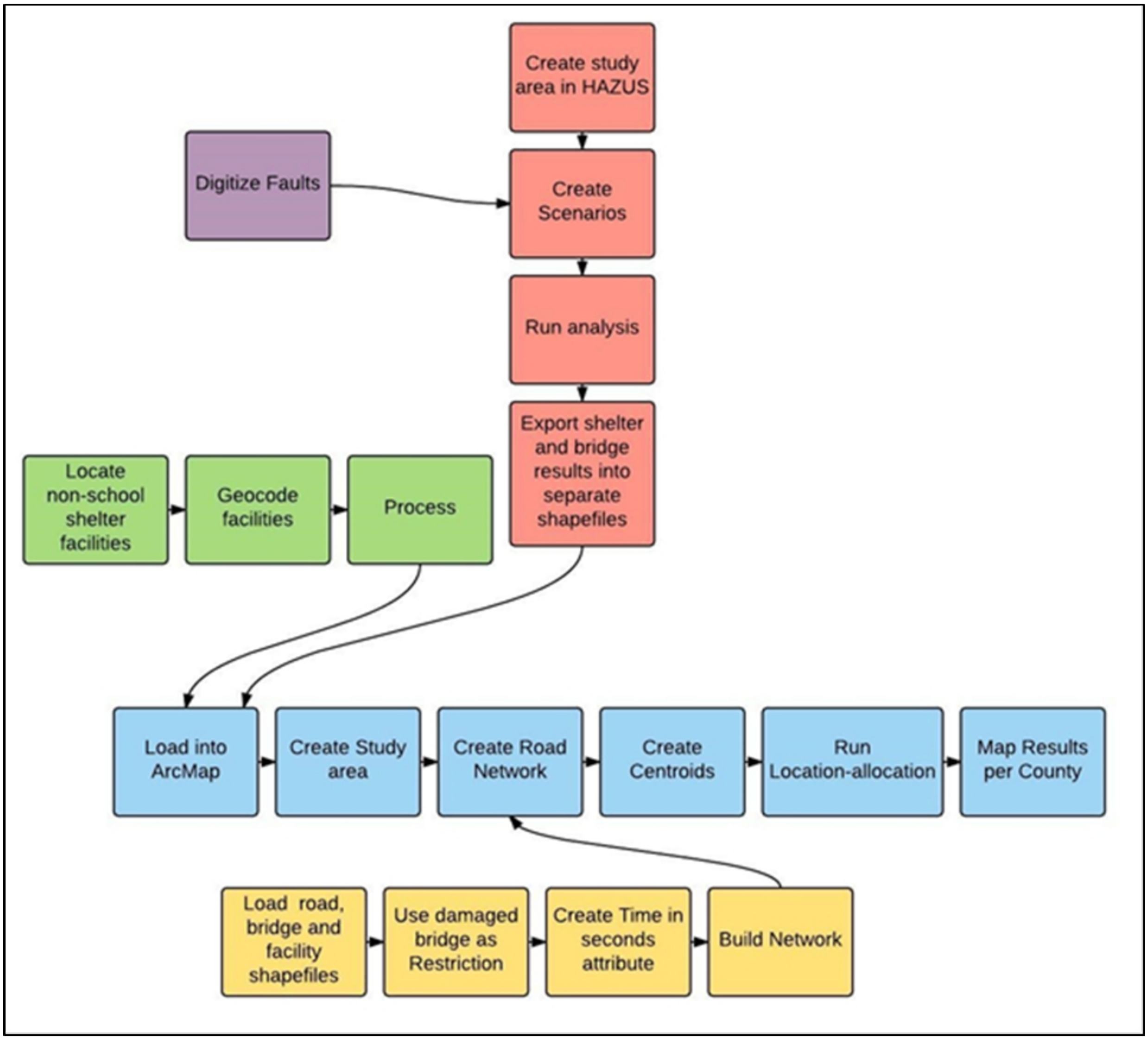

Figure 10 Flowchart of the methodology followed. Colors indicate the separate sections of the process described below.

3.2.1. Running HAZUS scenarios

For a scenario to be run, it requires the correct modules to be selected and a study area created. Tarrant and Dallas counties were loaded separately to accommodate two different fault lines and two different damage estimates. A scenario can be created from scratch by selecting the Arbitrary option, or a historic earthquake and its characteristics can be used by selecting the Historical event option.

Under the Hazards menu, a single scenario was created for each fault line. Each scenario used the same settings. Arbitrary was used instead of historical, as arbitrary allows for a hypothetical scenario with customized parameters. However, for scenarios in the Central U.S., the ability to customize is limited. For example, the attenuation menu (shown in Figure 11) does not allow any definition of fault type, likely due to the area not being known for earthquakes until the last 5 years. Fault rupture was also not available for specification.

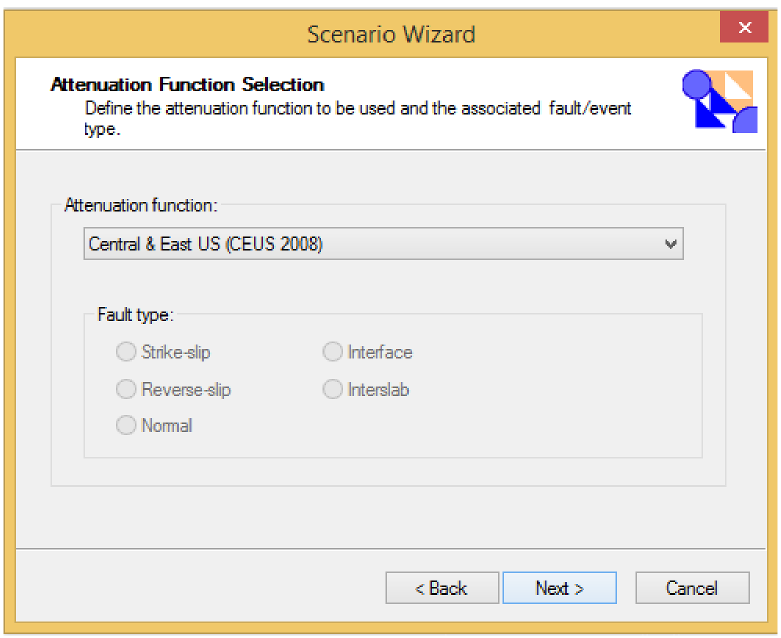

Figure 11 Attenuation menu

In the Scenario Wizard, the parameters for the earthquake on each fault were defined in the following steps: 1) fault lines were loaded into the scenario map, 2) the epicenter was chosen on the fault line, 3) magnitude was defined as 5.5, and 4) the depth was entered as 7 km (the average depth of historic earthquakes in the area). The fault lines for the study area were loaded into this map simply to guide placement of the epicenter which was chosen by clicking a point on the fault. The Azle fault was modeled only using Tarrant County, and the Irving fault only using Dallas County.

Once the scenarios were set, the Run menu was opened. All options for buildings other than user-defined and military installations (of which there were none) were selected as the interest was in the effects on all types of buildings and structures. For each county, the analysis took 7 to 10 minutes to run.

3.2.2. Extracting data from HAZUS results

After the results are ready in HAZUS, the map is not automatically shown as there are many options and variables that can be displayed. In the Results menu, options are given for every category. Any of these can be mapped by opening the attribute table selecting a column, and hitting the Map button. The maps produced in HAZUS are simple, such as shelter needs per census tract. More complex analysis requires ArcMap itself. For this project, Shelter needs and Road Transportation results were mapped and then exported into separate shapefiles for each scenario. The data inside these shapefiles include location, name, damage severity, percentage of damage that was a certain severity or above, and whether it is expected to be functional after a few days to a few weeks.

Bridges are the most important structure in determining which shelters are accessible, so determining at what damage threshold a bridge is unusable was critically important. Bridge data could only be acquired after running the scenario by mapping an attribute which creates a layer that includes all the data, and then exporting the whole file into shapefile format. In the bridge attribute table produced by a HAZUS model run, damage is categorized as slight, moderate, and severe. There are also fields that show the total percentage of damage at and above a severity level, such as At Least

Slight. For this project, bridge usability was determined by the At Least Moderate field with a value of 20% damaged. A separate shapefile for damaged bridges was created by selecting only the bridges with damage above the threshold stated previously from the overall bridge count. The road shapefiles include bridges as part of the road so including all bridges was not necessary. The damaged bridges, as well as shelters and census tract centroids, were then snapped to the combined road and highway shapefile. All this now allowed the creation of a network dataset, which is necessary for location-allocation modeling.

3.3 Using ArcMap for Network Analysis

Once HAZUS scenarios were run, the results were saved and exported as separate shapefiles, with all bridges, shelter, and school shapefiles generated for each county. Non-school shelter points collected earlier were joined with the school shelter points extracted from the HAZUS inventory. The road and highway shapefiles from the NTCOG were also combined. A lakes shapefile from ArcGIS Online was included for display purposes because Eagle Mountain Lake is a prominent feature near Azle and serves as a limiter for population and a barrier to transportation.

3.3.1. Creating the Network

A network allows for analysis that requires traveling, such as identifying routes and locating best facilities. Networks require road shapefiles, as well as any facilities and objects that may affect the road network. All point shapefiles must be snapped to the road shapefiles to be read as part of the network. It uses connectivity settings in order to determine the behavior of each structure on the network. Properties such as speed and length are used to determine travel time, while impedances block certain routes. Once the road's properties and general attributes are set, the network dataset can be built. The output dataset has junctions, which are the damaged bridges and schools, and edges which are the roads and highways. System junctions were where the roads intersect.

Potential damage to the schools was assessed as a limiting factor to their designation as shelters, but all had usability ratings of 80% or higher for the first day after the disaster. Thus, given that only 15% of the schools incurred any damage at all, potential damage was not considered relevant when assessing shelter accessibility. All potential shelters were included in the modeling.

To create the network, a database was built that included the locations of the damaged bridges, shelters, and road shapefiles for each county. Damaged bridges were selected from the original bridge shapefile using a moderate damage threshold of 20% and made into a separate shapefile. This was so it could be treated as an impediment. Generally, bridges were simply part of the road rather than a separate feature since a bridge just allows a road to cross over an obstacle. However, the damaged bridges serve as an impediment to travel, completely blocking a route that requires crossing the bridge. Thus they were junctions in the network acting as barriers. This is because if a bridge is damaged enough, it is not safe to drive over and alternative routes will need to be found.

Network edges have time and length attributes. Time is used to calculate the fastest route, while length is for calculating the shortest route. Other considerations normally assigned when building a network such as one way roads and U-turns were not included as police can override travel directions in case of emergencies. A section of the resulting network is shown in Figure 12. Damaged bridges were symbolized on top of junctions to show which junctions were the bridges and which were schools.

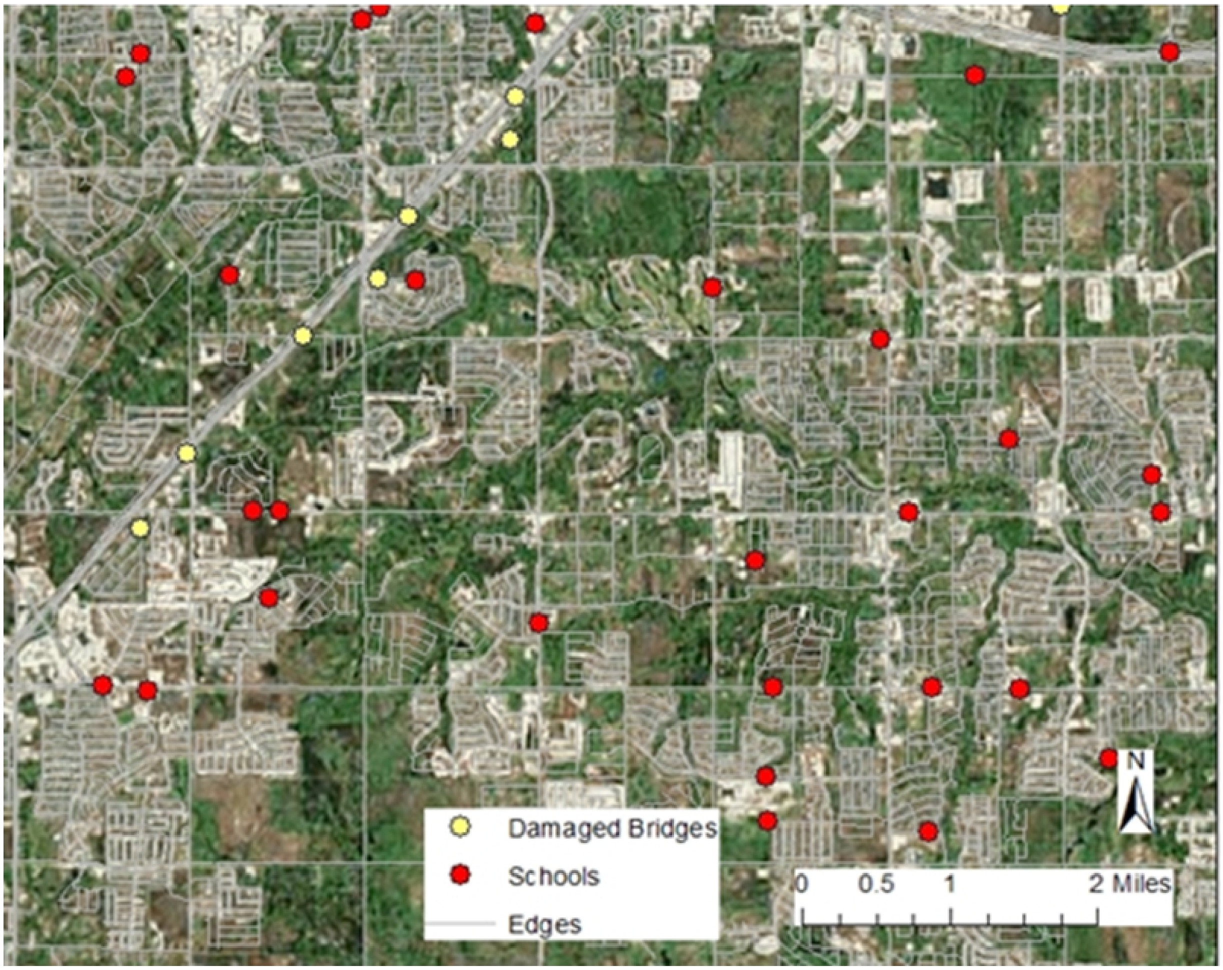

Figure 12 Small section of the road network

3.3.2. Location-Allocation

Location-allocation calculates the best destination point from each starting point given the objective of minimizing travel time over the network and accounting for capacity constraints at the destination. If a facility gets full, it will choose the next closest facility with available capacity. The built in impedance in the network may alter the destination by preventing the best route from being used since that route involves a barrier.

For this project, centroids of the census tracts were used as starting points since individual houses are not available in HAZUS. Thus they serve as a generalization of the starting point for all people within each census tract and are used to calculate the distance to shelter. The number of people needing shelter in each census tract was assigned to its centroid as the shelter demand quantity. Each shelter was given a capacity of 250. The damaged bridges shapefile was used as the point barriers so that travels times would be calculated correctly if it required going around an affected bridge. Prior to running the location-allocation tool, tract centroids, damaged bridges and shelter points must be snapped to the road network in order that road connections between origin and destination could be calculated.

Due to edge effect, it was anticipated that census tracts along the edges of each county would be allocated to the opposite side of the county where spare capacity may remain. Thus, additional schools from adjoining counties were exported from HAZUS, and then combined with the Tarrant and Dallas County schools before they were added to the network.

3.4 Summary

HAZUS was used to produce data to be input to the location-allocation model in ArcMap. An earthquake scenario was created for each fault. Bridge damage and shelter needs were acquired after the scenario was run. After exporting the bridge and school data, the schools were combined with the other potential shelter points collected earlier, and a road network was created that included the damaged bridges as point barriers. Census tract centroids were created and snapped to the network and a location-allocation analysis was run using the centroids as starting points and the set of potential shelters as the destination points. The results are shown in the next chapter.

Chapter 4 Results

This chapter is split into two parts: the results from HAZUS and the results from the location-allocation tool. HAZUS results include how many people need shelter, as well as the location of and damage estimates for bridges. Location-allocation results show the closest shelter location by travel time from each population starting point and available capacity.

4.1 HAZUS Results

Scenarios were run for both faults. Comparing the results, the 5.5 magnitude earthquake has a higher predicted impact on the Irving fault area in Dallas County area than on the Azle fault area in Tarrant County. Many of the bridges in Dallas County were predicted to have damage, with a large portion of the bridges in the northwest corner having a predicted damage rating of 70% for at least moderate damage, as seen in Figure 13. The fault runs right through this heavily populated area (shown in the upper left in the figure), which is home to multiple highways and a large amount of local streets.

Figure 14 shows the number of people in each census tract in Dallas County who may need shelter. This map is classified using natural breaks as there were breaks in the data, with people needing shelter jumping from 173 to the next closest number at 264. This was adjusted so that the lowest value is two or less since it was decided that with only a small number in a tract, they are not likely to need help finding shelter. Overall, the scenario estimated that a total of 12,820 people in this county would need temporary shelter if this event happens on the Irving fault. Shelter needs were projected to be significant in some areas, with one census tract possibly having 279 people with short term shelter needs, although this was also the largest tract. Three smaller tracts also had over 175 possibly needing shelter. On the other hand, most of the tracts have under 175 people needing shelter, which allows multiple tracts to be assigned to the same shelter with a capacity of 250.

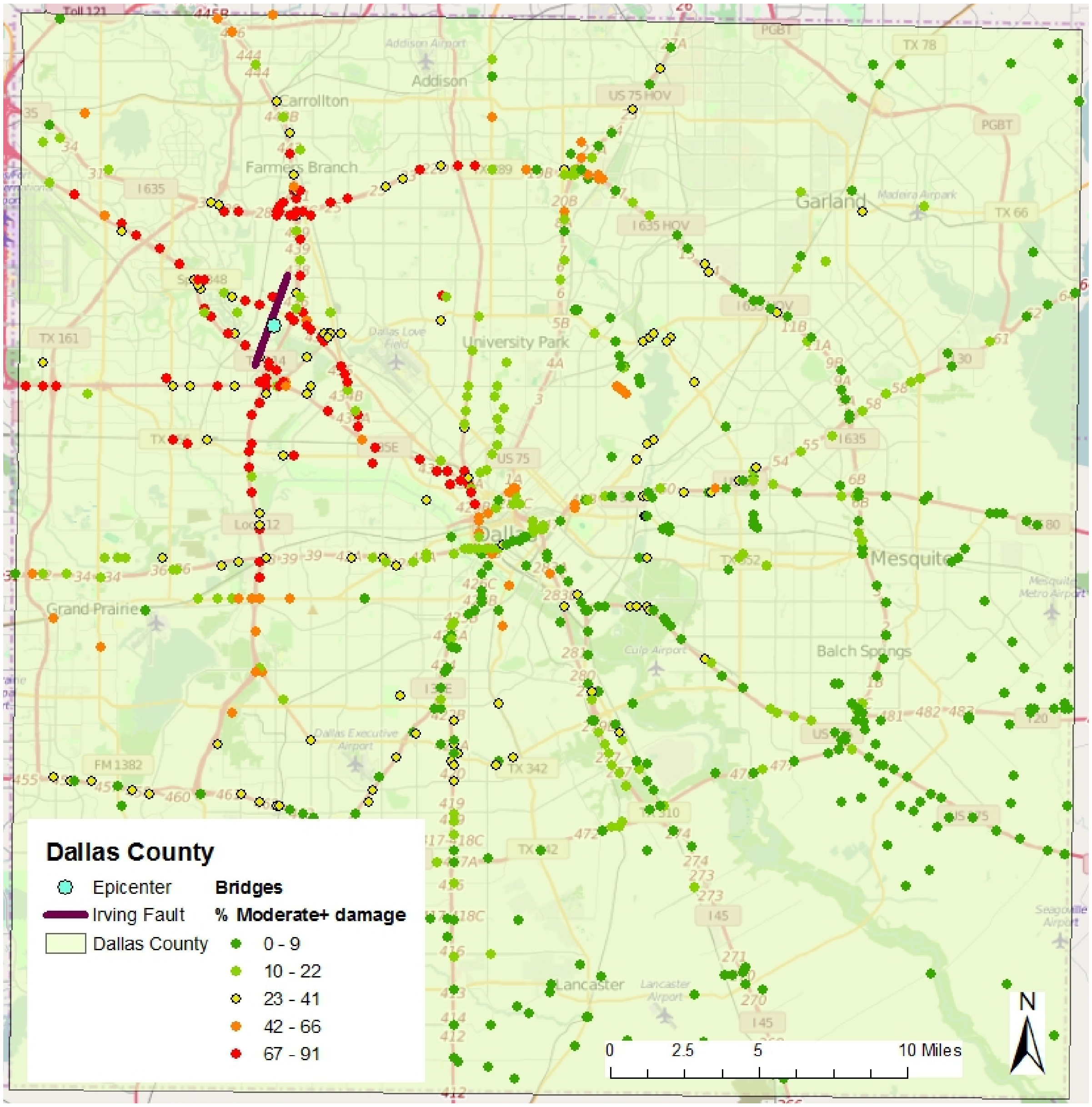

Figure 13 Bridge damage in Dallas County

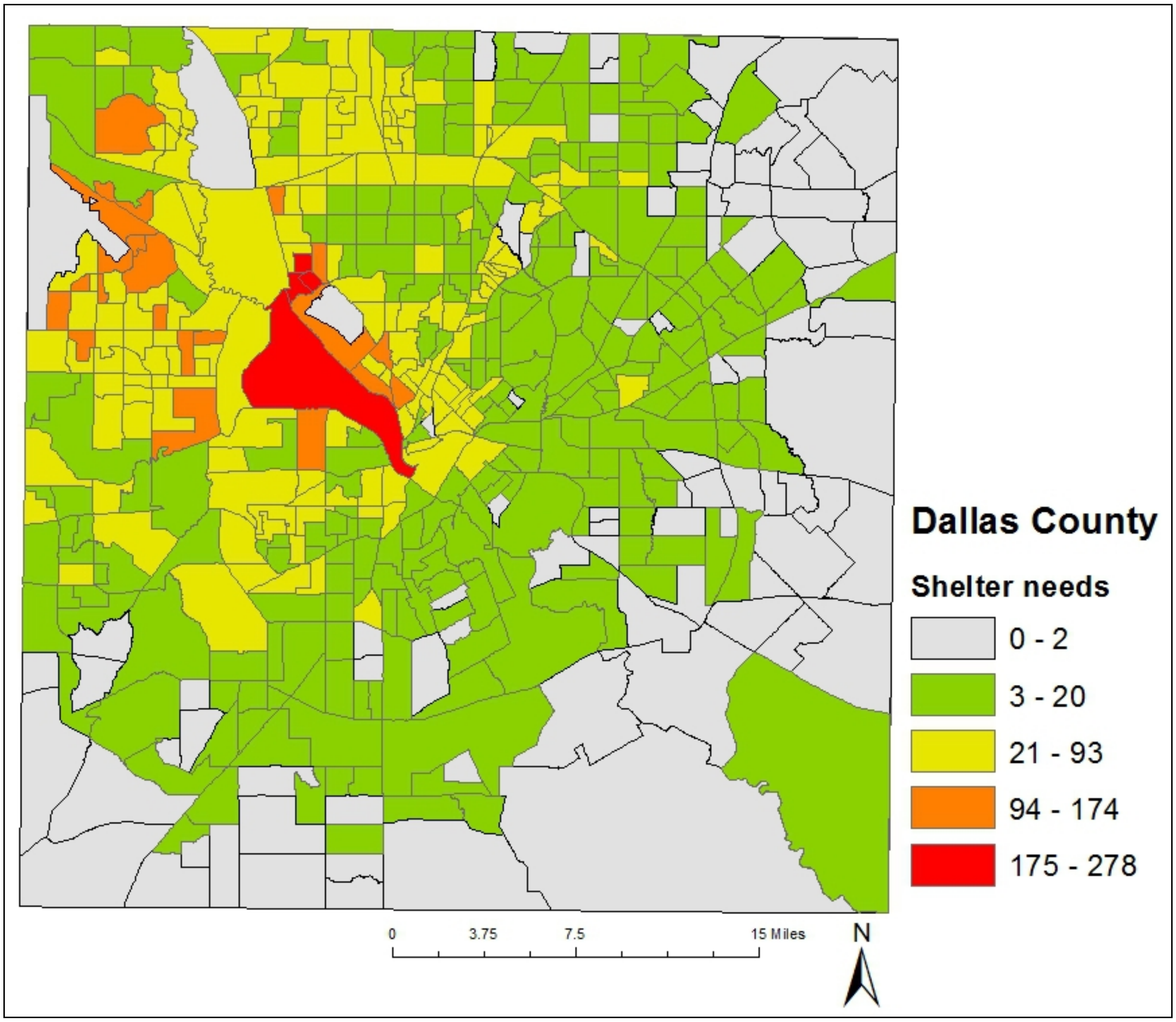

Figure 14 Shelter needs in Dallas. Map shows the number of people requiring shelter in each tract.

In Azle, the damage to the infrastructure and the population at large was predicted to be less severe. This is due to less population overall (10,000 as of 2010 Census), less population density, the lake being a natural barrier to growth and less transportation infrastructure. There is a distinct lack of bridges near the fault area in the northwest as well. As Figure 15 shows, the vast majority of bridges are predicted to be fine, but there are some areas where the bridges were given a moderate damage rating of 70% or more. A total of 1,011 people will need shelter as a result of the hypothetical earthquake event, with the highest number of 56 in one census tract (Figure 16). This map was also classified using natural breaks, as there were breaks in the data, going from 15 to 20 and again from 27 to 41 of people needing shelter.

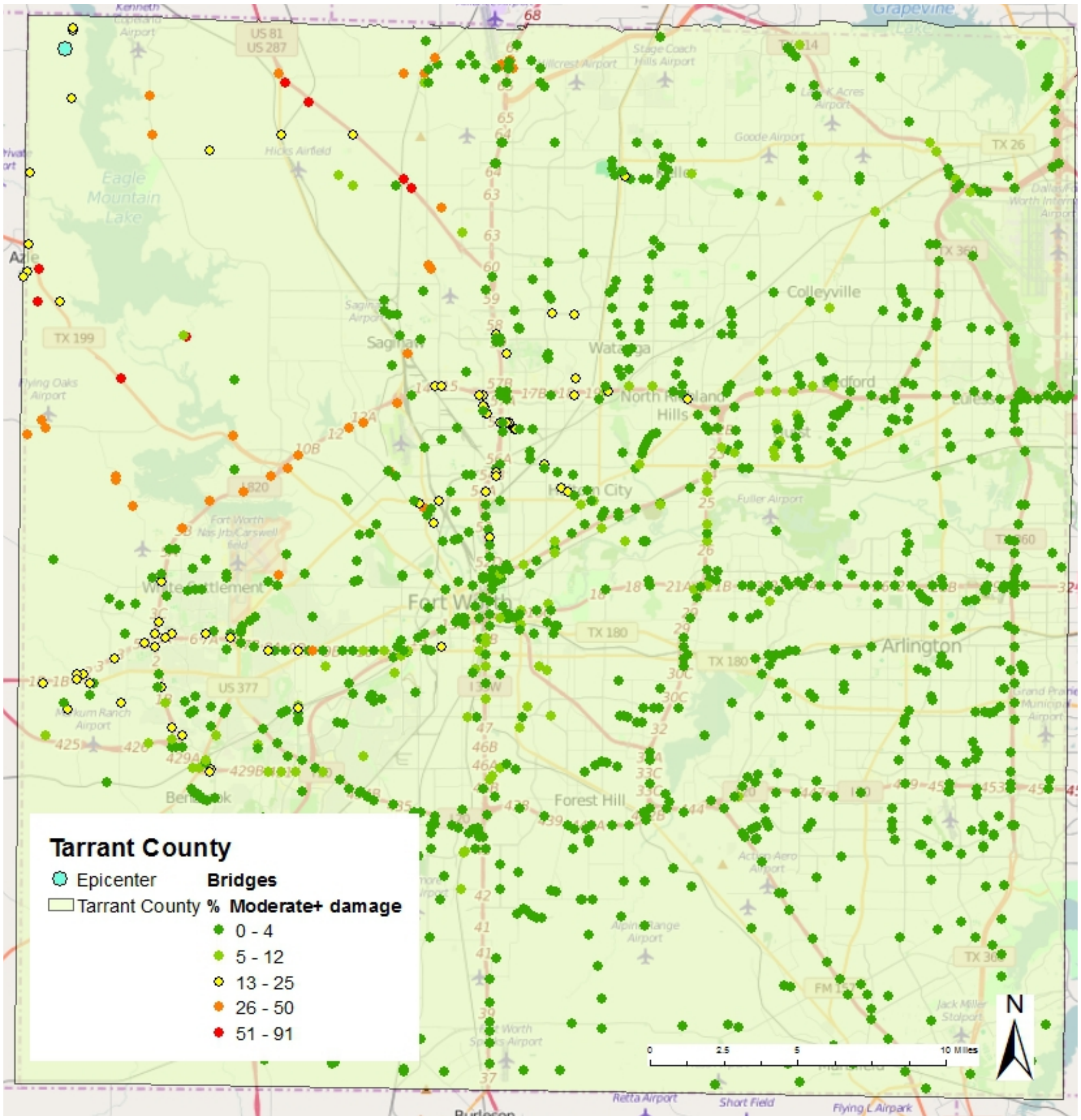

Figure 15 Bridge damage in Tarrant County

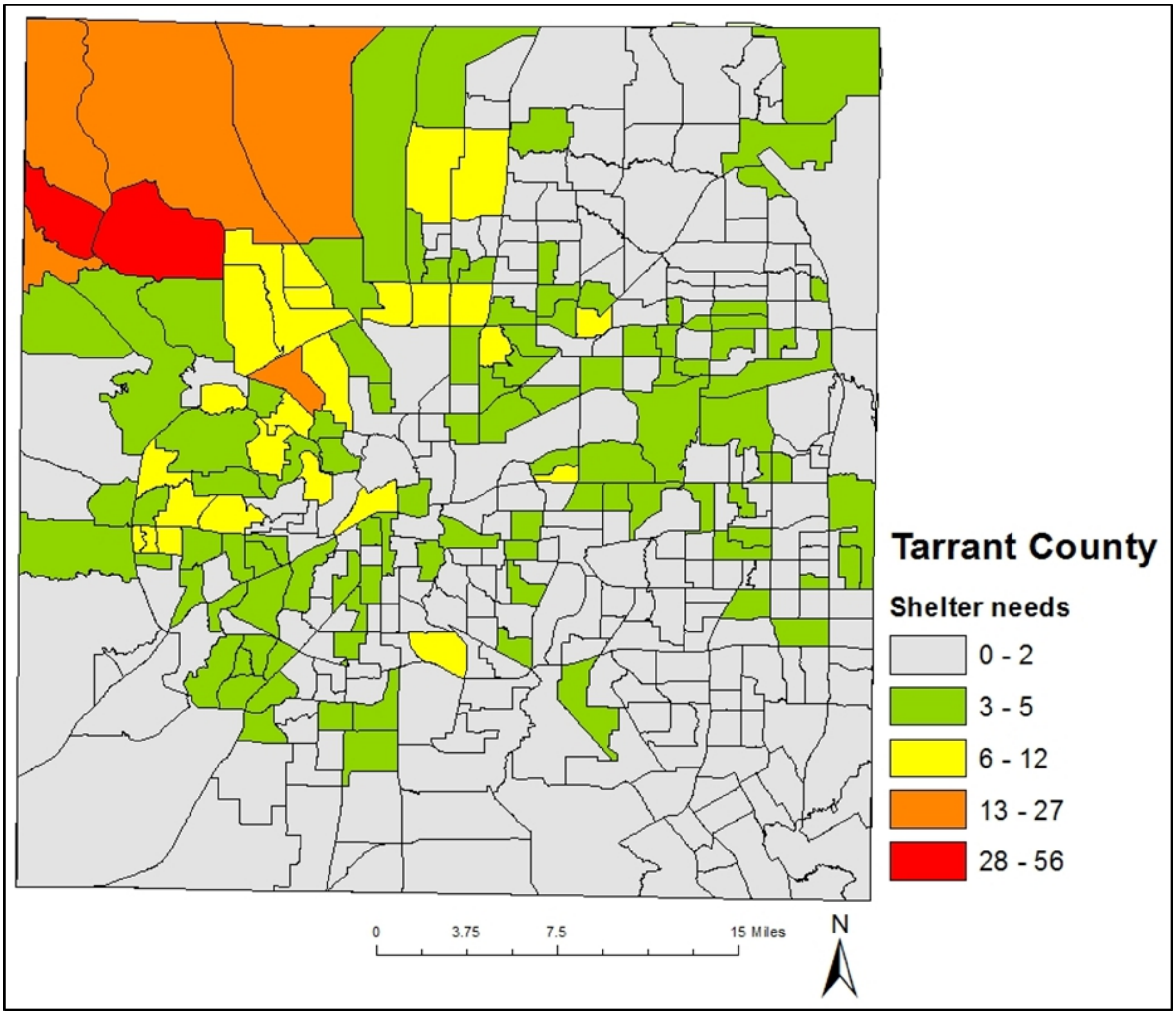

Figure 16 Shelter needs for Tarrant County. Map shows the number of people requiring shelter in each tract.

4.2 Allocation of Population Centers

While most tracts were allocated to shelters, several in Tarrant County and many in Dallas County were not. In Tarrant County, the remoteness of the area hit means there are less ways to get around, and thus one is more likely to be heavily affected if a bridge is unusable. Figure 17 shows several census tracts were not matched, even with the inclusion of shelters outside the county. Census tracts in the remote areas close to where the earthquake is located have low population densities of 199.5 and 402.1 per square mile respectively. The most heavily damaged bridges are around this area, as seen in Figure 15. The shelters that would be closer also most likely filled up from other, closer census tracts. The map output shows all candidate shelters, with the designated destinations symbolized differently. It also includes allocation lines to show which census tract was allocated to which shelter. Unallocated starting points are also shown.

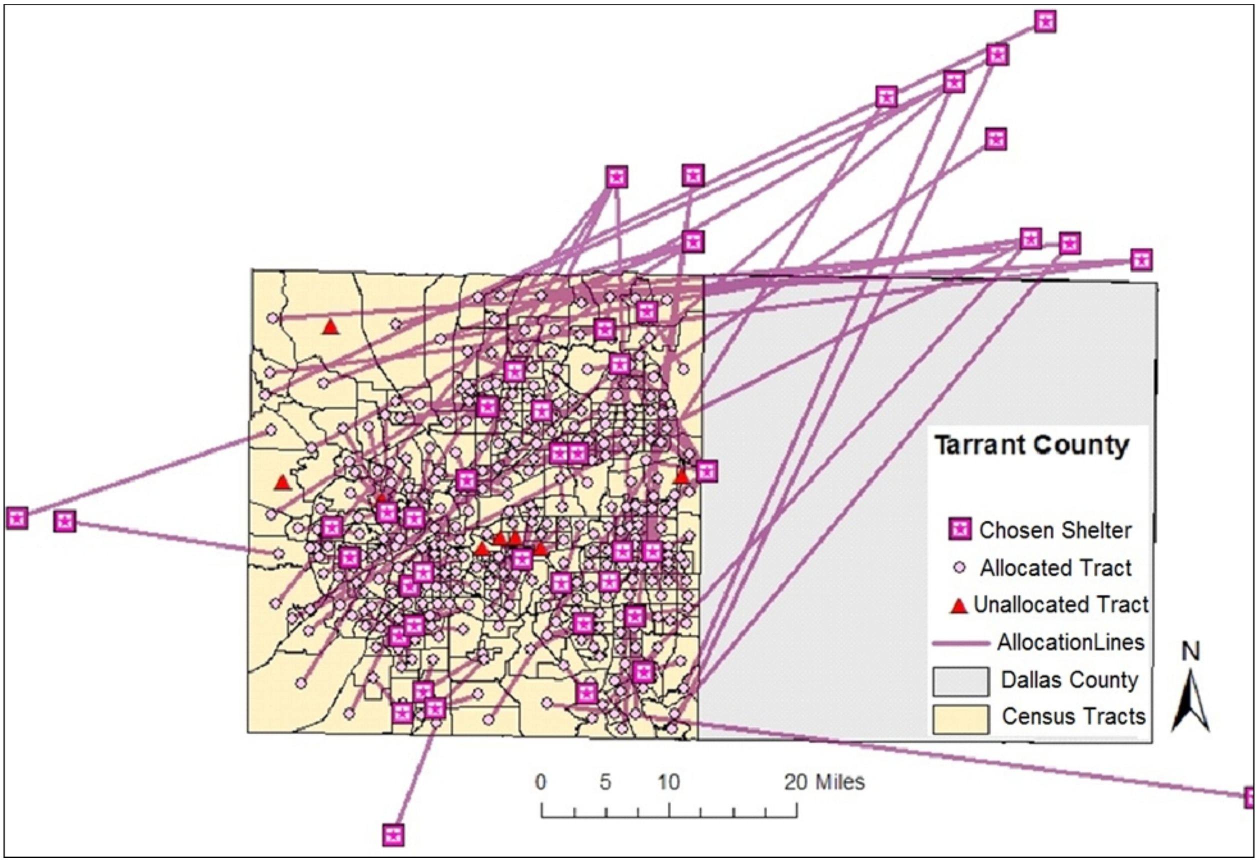

Figure 17 Allocation of tract centroids to shelters in Tarrant County

Dallas County also had unmatched points, as seen in Figure 18. These tracts were not edge cases, so it is likely the accessible shelters filled up. Many, however, have moderate shelter needs, as seen in Figure 19, so identifying shelters reachable by foot or ideal locations for more shelters would be the next step. Most other census tracts with moderate to high shelter needs were allocated within one to two tracts, so shelters would be reachable. Edge tracts were assigned to outside shelters, but many of them are far away from the origin point. Several of these have moderate shelter needs, so additional shelter locations may need to be identified in the future to avoid long travel times.

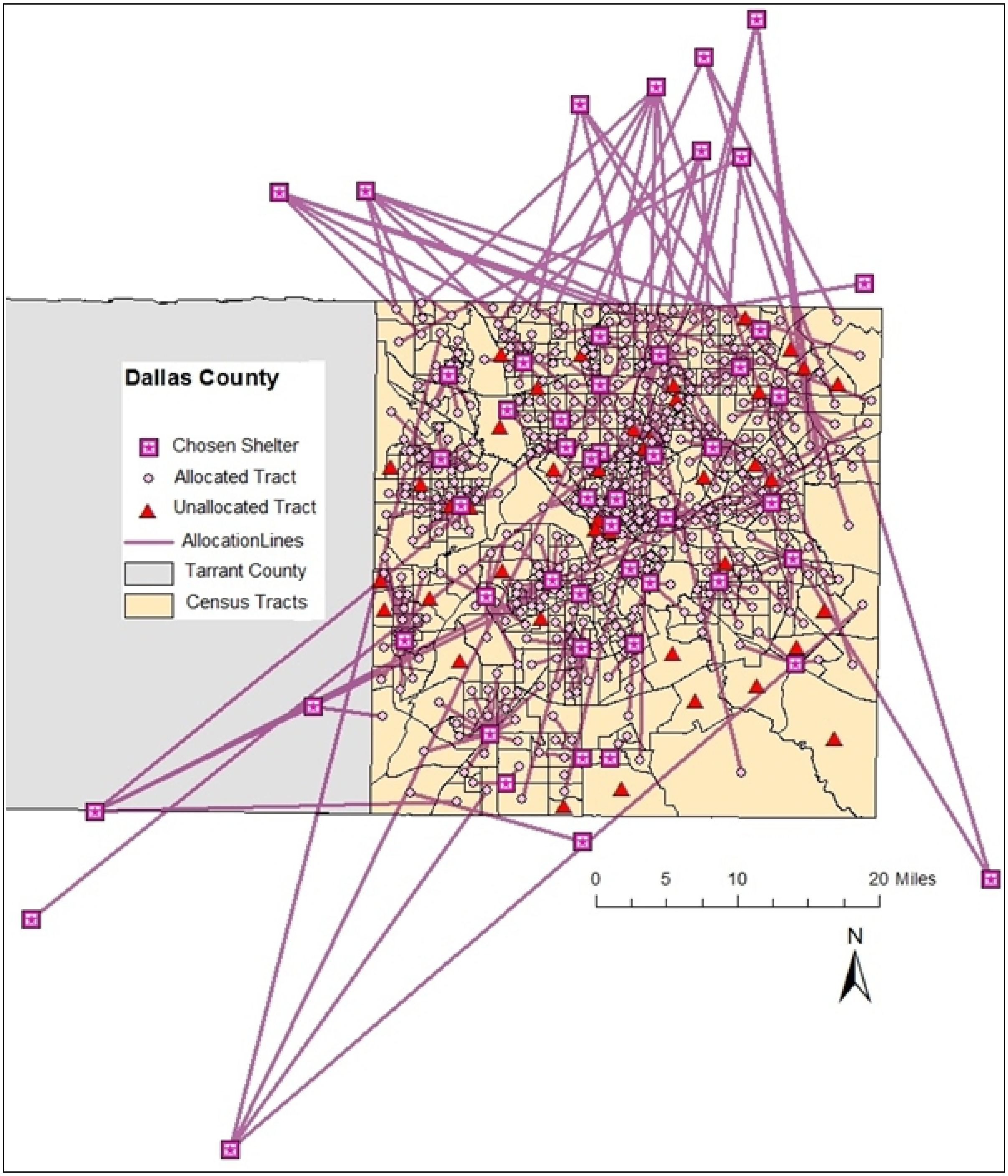

Figure 18: Allocation of tract centroids to shelters in Dallas County

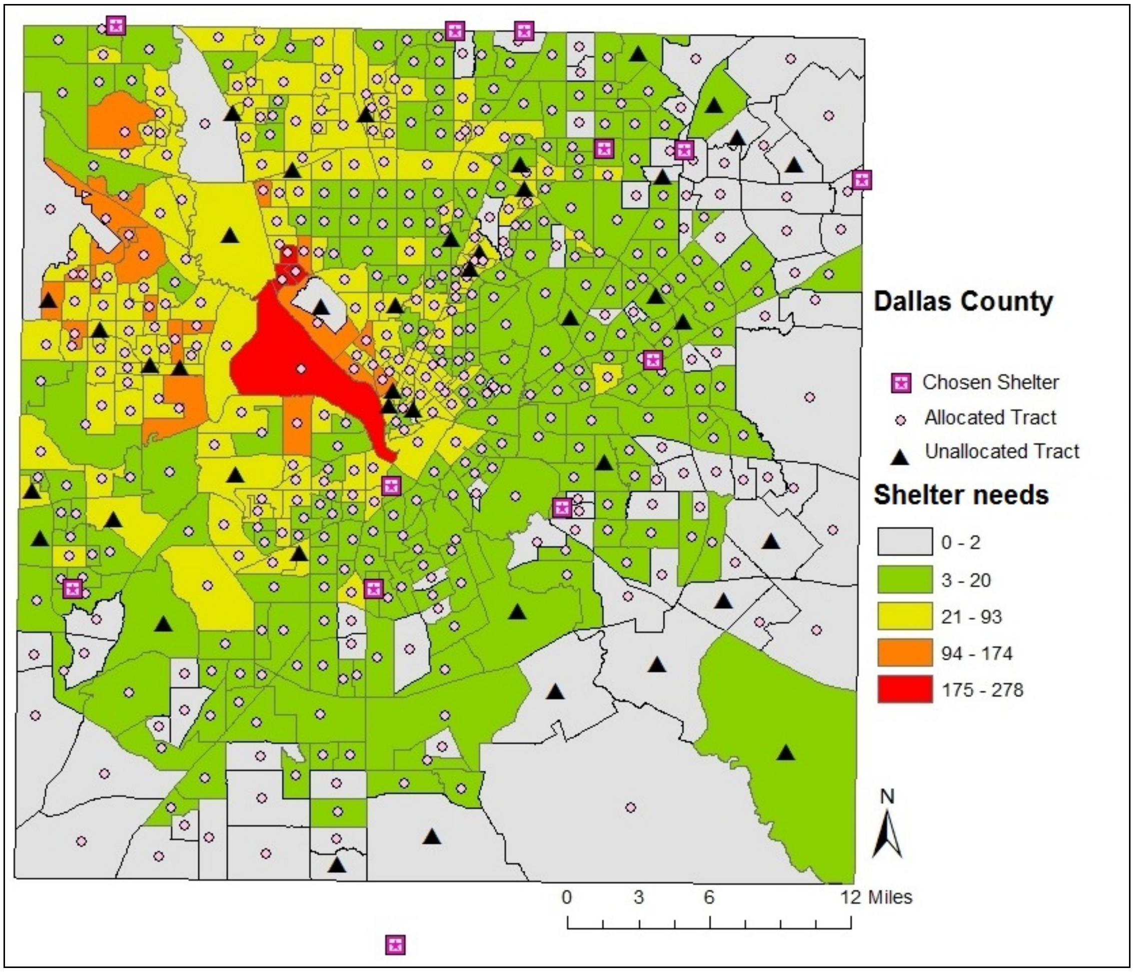

Figure 19: Unallocated points in crucial census tracts

Some census tracts in both Dallas and Tarrant Counties were allocated outside, and quite far into, those other counties. This analysis was conducted on time in seconds, not on length of travel. Due to highways having an average of 30 miles per hour increase over normal roads, these may have been quicker once the closer ones filled up. This may be because frequent stops on slower roads due to traffic lights and stop signs may not be as efficient as a fast, continuous highway if the highway is not blocked. Figure 20 shows how the tracts are allocated when using meters instead of seconds.

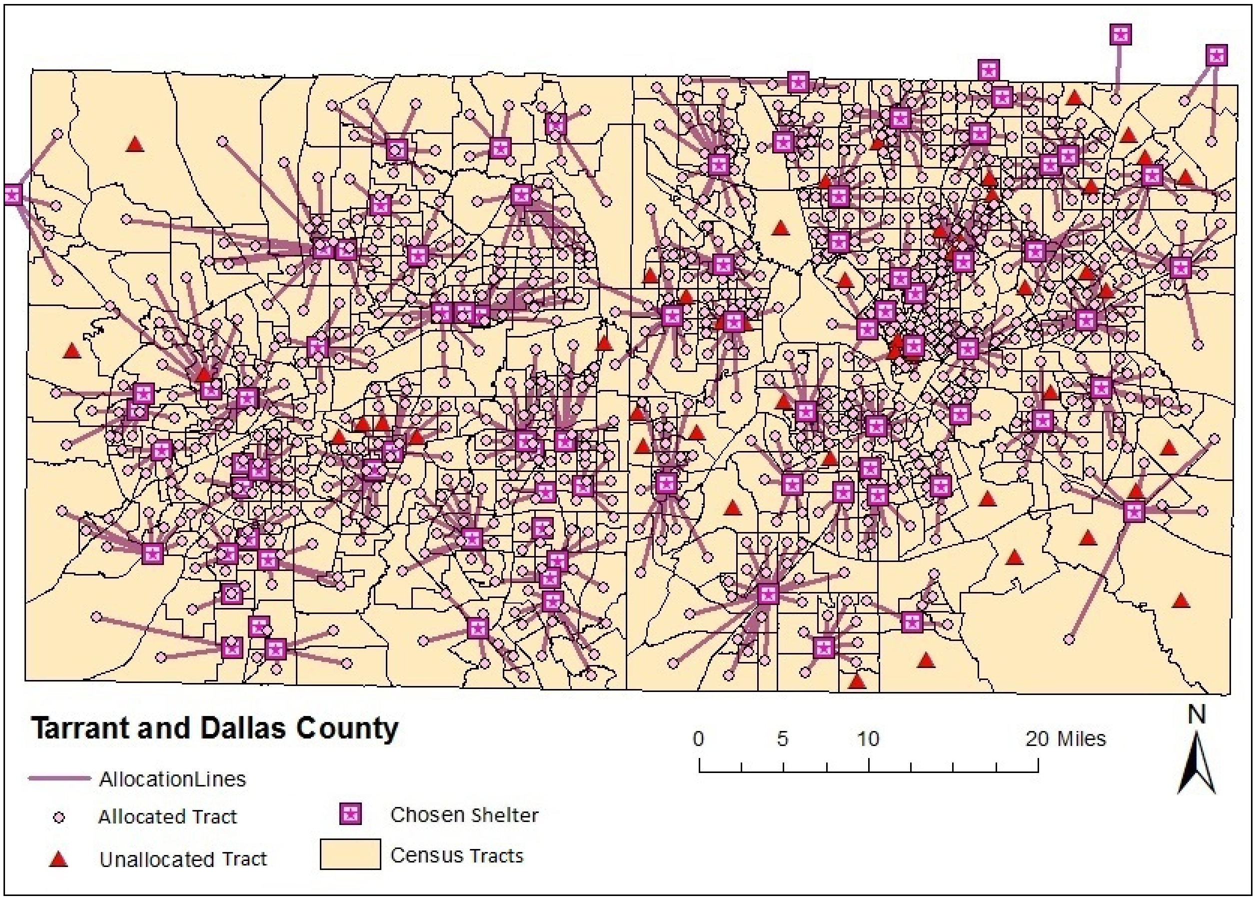

Figure 20: Allocation of census tracts by distance in meters

4.3 Summary

The HAZUS analysis showed that damage from these earthquake scenarios could be significant. Dallas County had many of its bridges damaged, and over 12,000 people would need shelter. While many of the shelter needs in census tracts that were impacted moderately or above were able to be allocated, others were not. This may be due to capacity being filled at all the reachable shelters. Azle was less impacted, likely due to a decreased population density, but 1,000 people still needed housing in shelters. There are far fewer bridges in the area but the ones that are there had mostly moderate or above damage. Some census tracts in Tarrant County were also unallocated, also likely due to capacity issues combined with whether it could be reached at all. Census tracts allocated far into other counties may be due to it being faster to travel to them by highway with no damaged bridges rather than use many small roads to shelters that are less far away. These results may have significant implications if an event were to actually occur, and this is discussed in Chapter 5.

Chapter 5 Conclusion

HAZUS showed that there is potential for damage from a moderate earthquake on the newly discovered faults. From this, the combination of HAZUS and location-allocation can be useful to understand shelter needs as a result of the simulation, and which shelters should be used. Results from HAZUS were incorporated into ArcMap to build a road network and run the location-allocation model. This allowed a visualization of which shelters were allocated to which census tracts, and whether some could not find any available shelter. Such an approach can assist city emergency response planners to better address their community shelter needs in the event of a disaster, such as the earthquake in this project.

5.1 Implication of these results

Running HAZUS showed that the damage from a 5.5 magnitude earthquake could be significant to the road network as well as to residential homes. A total of over 12,000 were predicted to need shelter in Dallas County, compared to just over 1,000 for Tarrant County. Many more bridges were predicted to suffer from a significant amount of moderate or above damage in comparison as well.

Bridges are a crucial component in transportation, and are especially vital in areas such as North Texas that rely on a lot of highways and have a dense road network. Running HAZUS on a simulated 5.5 earthquake showed the possibility of many of the bridges in Dallas County suffering significant moderate damage. This was assumed to have made the bridges unusable in the analysis conducted. If the simulation holds true, strengthening key bridges should then be prioritized to increase route availability. If the bridge data in remote areas are accurate in where they are damaged, local government could send out engineers to determine if it is possible at all to get people across. This is because simulation is not necessarily fact, and bridges may be affected differently than the simulation implies. There could also be routes built specifically for such emergencies that wouldn't need to travel over or under bridges at all. This would allow people to travel to shelters without encountering road blocks from out of service bridges.

While most census tracts were able to be matched, several were not and this is concerning. Damaged bridges in remote areas where there aren't a lot of alternative routes had a significant effect. Including shelters from outside the county did not seem to help either these or the census tracts on the edge of Tarrant county, even though it is the next most logical step if local shelters are unavailable. This suggests a need to address transportation issues at the local level to get to acceptable shelter. Otherwise, most of the other census tracts with heavy shelter needs were able to find shelter within a reasonable distance of one to two census tracts. Census tracts being allocated farther away than one or two census tracts may suggest that it would be better to open up new shelters close by that wont be slower to get to than hopping on a useable highway and driving farther, but quicker. Local governments could identify which structures would serve well as shelters that also avoid as many bridges as possible. If none could be identified, they could also build or designate additional structures that community's needs. This last is especially important for rural areas, and may be the main way to address the completely unallocated census tracts. Overall, the results showed there may not be enough shelters without extensive driving.

5.2 Limitations

The project does have some limitations. Primarily, scenarios and models can only approximate damage and its impact, with the accuracy depending on how much the data reflects reality in ground movement and the composition of buildings. It cannot say what will happen, only what can happen. It is then up to city planners whether the possible risk is worth acting on or not. HAZUS inventory is extensive, but it is updated only every few years. This limits accuracy without extensive local knowledge, and so damage estimates may be more inaccurate than what would be acceptable for municipalities. FEMA does allow user input into HAZUS and adjusting the state dataset though their Comprehensive Data Management System (CDMS) tool, but that was not utilized in this project. Ideally, this project would have used that tool to make a more accurate representation of the study area. In addition, it would be beneficial to include the counties around the study area to see how far the damage may have extended into those areas.

The location-allocation tool does not provide the routes between source and shelter, only which available location is the closest destination. Including the routes through use of other tools would be beneficial in a future study for those who may not know how to get to the suggested designated shelter for their census tract.

The results for distance versus time location-allocation show that there is a large discrepancy on closest available shelters between the methods. This project focused on time as the measure of closeness, which would be appropriate for people with vehicles. The distance solution that was briefly tested did allocate some people more than a census tract or two away, which might be a very long walk. Future efforts should explore the distance solution further in an effort to constrain the travel distance by foot for those without a vehicle.

The value of this research is in informing city planners of what may happen in the event of a moderate earthquake, where acceptable shelters are for each census tract, and if there would be any census tracts that may need additional shelters from not being allocated to any current shelters. Census tracts that were unallocated would be the most important to address, with the planners taking steps to address the problem. The HAZUS simulation can also be used by engineers to identify bridges that may be issues after a disaster, and to fortify them before an event occurs. Overall, it serves as a way to demonstrate to city planners the possible effects of an earthquake, possible shelter needs, and where or if people can get to shelter

5.3 Future Research

There are several ways that further studies can expand on this project. While this document focused on the DFW area, Oklahoma has had the most severe and most numerous of the earthquakes that have occurred. The highest was a magnitude 5.6 44 miles East – Northeast of Oklahoma City (USGS 2011).With a magnitude close to this project's scenario having actually occurred, identifying shelters would be very important if the epicenter happened closer to Oklahoma City (OKC), which has a higher population than the rural area where the earthquake occurred. This project could serve as a framework to apply the same methodologies to OKC.

The HAZUS portion could also be used to identify possible problematic bridges for engineers to fix. With American infrastructure not being adequately kept up, and bridges having a C+ grade with the occasional collapse (Swearington 2015), it is critically important to know what bridges may suffer enough damage to make it impassable, how important that bridge is to the overall traffic flow, and to fortify it ahead of time.

While this study is useful as a demonstration of capabilities, in order to turn this study into a highly detailed, localized Level 3 HAZUS analysis appropriate for full emergency preparedness exercises, some additional information would need to be acquired and added. These include:

1. Detailed soil maps that can give a better damage analysis resulting from ground shaking, as the default in HAZUS uses very generalized soil descriptions and classifications.
2. Ground motion equations appropriate to the area should be used instead of the default provided for the CEUS area.
3. The user should also load their own inventory of local buildings for improved accuracy, as HAZUS only updates every few years.

Overall, this project showed how it is possible to determine which shelters may be accessible using the location-allocation tool, with HAZUS providing the damage impact to the road structure and population displacement. Counties are interconnected through their road networks, so it was necessary to include outside shelters for edge census tracts to travel to if possible. City planners and engineers can use the study as demonstration of how to assign people to shelters and to identify places where shelters may not be available, whether due to not enough capacity or too much damage to the road network. Whether it is better to find a close shelter or to get to a shelter as soon as possible should also be explored. It is the hope that this project can serve as a framework to encourage other areas vulnerable to earthquakes where they have been historically very rare, such as Oklahoma City, to explore the potential damage through tools such as HAZUS and Location-Allocation.

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