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Hazard Analysis of Interdependent Infrastructure: Case Study of the Denver Region

Alena Christine Rein
University of Colorado at Boulder, alena.rein@gmail.com

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Hazard Analysis of Interdependent Infrastructure:
Case Study of the Denver Region

by

ALENA CHRISTINE REIN

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Hazard Analysis of Interdependent Infrastructure: Case Study of the Denver Region

written by Alena Rein

has been approved for the Department of Civil and Environmental Engineering

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Professor Ross Corotis, Ph.D., P.E.

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Professor Abbie Liel, Ph.D., P.E.

____

Professor Nevis Cook, Ph.D., P.E.

Date_____________

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The final copy of this thesis has been examined by the signatories, and we find that both the content and the form meet acceptable presentation standards of scholarly work in the above mentioned discipline

Rein, Alena (M.S. Civil and Environmental Engineering)

Hazard Analysis of Interdependent Infrastructure: Case Study of the Denver Region

Thesis directed by Professor Ross Corotis

Interdependencies amongst infrastructure systems including transportation, water, electrical, and communication systems have increased drastically with the rising level of complexity in developed cities. Previously independent systems now heavily rely on the interconnections between reliant systems. As complex networks have evolved, they have magnified existing levels of vulnerability in densely populated areas. These interdependencies must be identified and addressed, requiring extensive communication among planning agencies and organizations at all levels: federal, state and local. The Denver Region in Colorado, USA is used as an example case study showing several of the existing physical and geographical interdependencies (using the program, ArcGIS, developed by ESRI), and looking at how future development plans, anticipating an estimated increase in population growth, are heightening current vulnerability levels. The criticality of these identified interdependencies is shown by discussing the effects from potential stressors prevalent to the Denver Region, including an earthquake, flooding, and the transportation of hazardous materials along a major corridor. Additionally, the type and frequency of communication between key planning agencies and organizations in the Denver Region is investigated through a survey to determine if the potential threat from natural disasters, man-made hazards, intentional attack or population growth are key topics being communicated in order to ensure that the possible effects of these stressors on the existing systemic interdependencies are being addressed. Case studies at a local level are critical in understanding the infrastructure network connecting adjacent regions as well as on a nationwide level. In addition, Interviews were conducted with key personnel in several Denver regional agencies in order to directly reveal their views on interdependencies among various infrastructure systems and emergency preparedness strategies.

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Introduction

1.1 Background

Infrastructure systems, including transportation, electrical, water, and communication systems, have rapidly developed over the years. The progressive development of each of these systems has become beneficial to each individual system itself, but has become increasingly unfavorable for the infrastructure as a whole in terms of vulnerability. Infrastructure interdependency can be defined as individual infrastructure systems relying upon one another to function properly at their intended capacity. The dependencies among these systems have grown to a point where the overlapping systems' networks are so complex that many of the interdependencies created cannot be defined. It is only when an unexpected event occurs that these nodal points of interdependency are discovered. Looking simply at where these systems are coupled and focusing on how to decouple these ties is not enough to reduce the vulnerability level. It is not possible to identify every location where these systems rely heavily on each other to operate, and some dependencies may only exist when human error is taken into account. In order to promote a sustainable development that is self reliant and resilient, each system must be evaluated individually and redesigned to separate under certain conditions. Otherwise, these interdependent connections will continue to loom, awaiting for a disaster to strike. For instance, if an earthquake were to cause a bridge to collapse over a main highway typically used for transporting fuel, this would not only upset the traffic flow but would also hurt emergency electrical power generation by not being able to provide the fuel required to run the generators. A disruption in the electric grid could result in a failure of the communication system, essential to emergency response teams. Water systems could also potentially suffer from the effects of power loss with computer controls disabled by this loss, preventing proper water treatment. The failure of one system cascades into the failure of others, a clear indication that the entire infrastructure needs to be studied from the prospective of robustness.

Critical infrastructures are defined in the Presidential Decision Directive/NSC-63 as, “those physical and cyber-based systems essential to the minimum operations of the economy and government. They include, but are not limited to, telecommunications, energy, banking and finance, transportation, water systems and emergency services, both governmental and private” (Clinton 1998). Figure 1.1 was created for the current study from the fourteen infrastructure systems identified by Quirk and Saeger in “Robustness of Interdependent Infrastructure Systems” (Quirk & Saeger 2005). The interconnections were produced for this figure based on an assessment of their dependencies, creating the complex network of interconnections displayed.

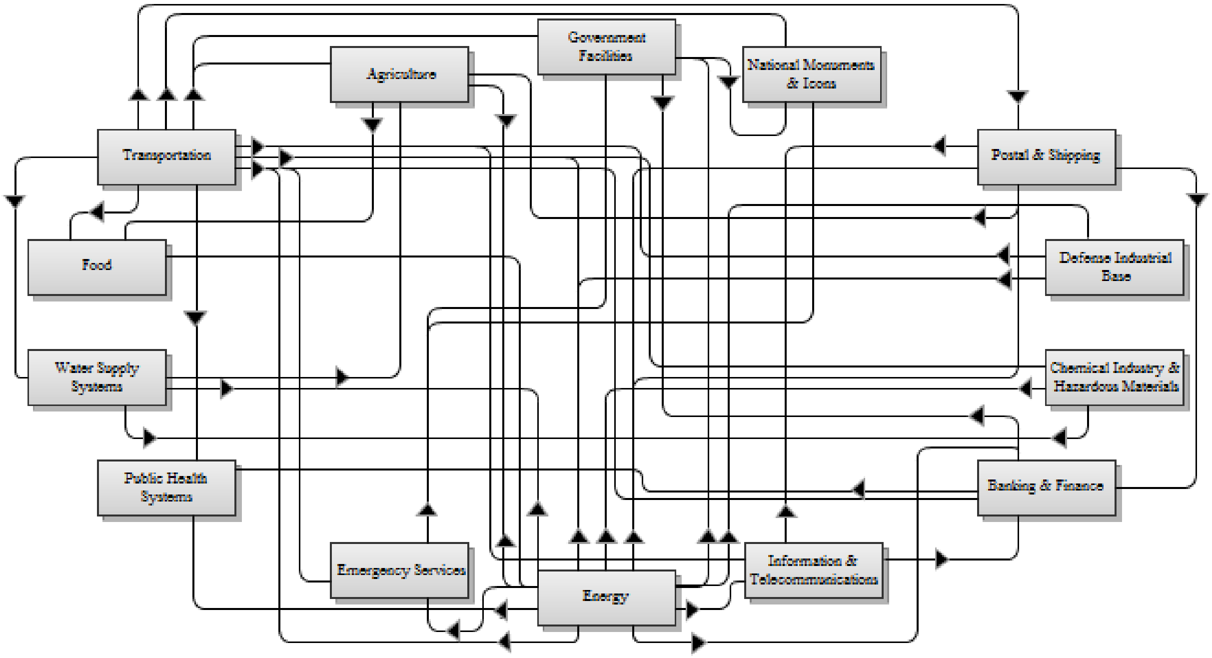


Figure 1.1: Interconnections among the fourteen infrastructures

Prior to the ubiquitous availability of computer technology, each of the infrastructure systems was relatively independent. Over the past two decades there has been an extensive transition from independent to interdependent systems. Information systems developed from computer technology are integrated wherever possible to promote efficiency and effectiveness. Examples of the integration of computer technology in infrastructure include the transportation system with real time data input to traffic signals controlling traffic flow, and water treatment facilities with computer controls. Unfortunately, this goal of increasing efficiency coincides with an increasing level of vulnerability.

Hindsight is an inevitable part of progress. Advancements in new technology are exciting and popular, but sometimes quickly accepted without time for thorough investigation of hidden effects. The ideas of speeding up production, creating new products, faster travel and communication, etc., screen the public from understanding how the advancements are adding to an already complex system that controls the way infrastructure operates. Not until a disastrous event occurs is the current system often proven to have vulnerabilities. Idealistically, if all systems were resistant to any damage, and ran perfectly smooth, then having them highly integrated would be most economically efficient. Today, with natural disasters affecting increased urban densities and intentional attacks becoming more prevalent, integration can now be the culprit in increasing the level of large scale potential failure.

Why is addressing the current design of the infrastructure system more important now than ever? There are several reasons to address this question; first and foremost, the number of lives currently at risk is very high, and due to continued urbanization will likely not decrease. In fact, according to the U.S. Census Bureau, “the Nation’s population is projected to increase to 392 million by 2050 – more than a 50 percent increase from the 1990 population size” (Day 2010). Cities around the United States have found a way to become denser by increasing the building heights, the complexity of the transportation system, and the ability to provide fuel, food, and other goods from outside locations. The occurrence of an earthquake along a fault line running through a major city could result in a catastrophic number of deaths and economic loss, incomparable to the event of an earthquake through a less populated area in a rural location.

Second, after the terrorist attack on the World Trade Center in September 2001, national security has become a strong focus. By having all of the critical infrastructure systems interdependent, an attack on one system subsequently affects all other systems, making it far too simple for a terrorist attack to cripple an entire city and adjacent regions.

Third, the total debt held by the United States prevents the government from affording the economic loss corresponding to a disaster. According to www.treasurydirect.gov, the total public debt outstanding at the end of 2010 stands at slightly over $14 trillion. Every disaster contributes significantly to the overall debt. For example, in the case of Hurricane Katrina in 2005, the Bush Administration “sought $105 billion for repairs and reconstruction in the region” (Onge & Epstein 2006). Placing the economic effect into further perspective, the 2010 fourth quarter figure for gross domestic product (GDP) in the United States was 3.1 percent (Trading Economics 2010). Hurricane Katrina decreased the national economic growth between 0.5 percent and 1.0 percent from the second half of 2005, significantly impacting the overall economy of the United States (Cashell & Labonte 2005). The current rate of growth in the GDP is not sufficient to to prevent the possibility of a recession resulting from another natural disaster with the same economic impact as Hurricane Katrina.

Fourth, rapid climate change has become a more recently recognized world issue. Weather and related factors are already incorporated into infrastructure design, including the forces accounted for, the materials used, and the design lives of structures. Climate change alters these assumed factors and could “shock” the system (NRC 2008). The degree of complexity of the infrastructure system and the sensitivity from these four factors as well as others portends a greater economic loss induced by a future failure of the system.

Interdependencies appear in four different forms: geographical, physical, cyber and logical (Quirk & Saeger 2005). Spatial proximity lends to geographical interdependency. Physical interdependency corresponds to the material input and output from one infrastructure to another. Cyber interdependency is based on essential data transmission. Logical dependency stems from human decisions, “a control schema that links agents from one infrastructure to agents from another infrastructure …an example is the logical interdependency between the electric power and financial infrastructures. In California, the deregulation legislation had influenced both infrastructures and induced the power crisis in the state in late 2000" (Quirk & Saeger 2005).

In the Denver Region, each of these types of interdependencies coexists. Although each of the four forms of interdependencies is important, the focus for this thesis primarily encompasses the geographical and physical interdependencies within the Denver Region, and identifying locations of vulnerability.

1.2 Scope of Thesis

It is only a matter of time befor the Denver Region to experience a major disaster, whether natural, man-made or intentional, causing significant damage and disruption to the region. Due to the complexity of major cities today, mitigation plans are a mandatory component in minimizing this potential harm. A beneficial way of developing a strong mitigation plan is to observe past cases showing the intimate connection between the infrastructure systems, and how these seemingly efficient interconnections heighten the level of vulnerability. The objective of this thesis is to first increase the awareness of the dangers associated with the interdependencies amongst infrastructure systems, then show the Denver Region as a case study displaying the potential risks from the possible consequences due to various stressors and the level social vulnerability within the region, and last emphasize the importance of interagency communication and coordination in hazard mitigation efforts. Chapter 2 takes a close look at three individual case studies from recent events that took place in the United States, demonstrating the cascading effect from one default in the infrastructure system to another. Chapter 3 presents four different methodologies of assessing risk: hierarchical holograph modeling, an optimization based methodology, and inoperability input-output modeling. Chapter 4 presents the application of using geographical information systems (GIS) as a planning tool used to physically and geographically identify interdependencies and vulnerable areas. Chapter 5 follows from chapter 4 by introducing a loss-estimation program called HAZUS developed by the Federal Emergency Management Agency to be used in conjunction with ArcGIS to simulate natural disasters, including earthquakes, flooding and wind. The application of using HAZUS to simulate two earthquake scenarios in the Denver Region is described in this chapter. Chapter 6 identifies several stressors (natural, man-made, and intentional) that are relevant to the Denver Region. In particular, the publicly accepted misconception that an earthquake occurring in Colorado directly affecting Denver would never happen is explored. Chapter 7 investigates several scenarios with the potential to render severe damage and disruption to the Denver Region. First, two earthquake scenarios are simulated using HAZUS and ArcGIS to identify specific locations within the region where extensive physical and economical damage is likely to occur. These identified areas are then compared to areas with social vulnerability to see where they overlap. Understanding where specific areas are prone to physical and social vulnerabilities is essential in developing proper mitigation plans to reduce the associated risks assigned to these locations. Second, flooding (a well known hazard in the Denver Region) is briefly examined to highlight the issues associated with promoting urban growth in designated flood zones. Third, the transportation of hazardous materials through the heart of Denver is investigated by looking at example accident scenarios at five specific locations along one of Denver’s major highway corridors (Interstate-25), showing the possible repercussions of allowing hazardous materials to be transported through a densely populated area. Fourth, population growth within the Denver Region is recognized as a stressor magnifying already vulnerable areas. Chapter 8 discusses the results of a survey focused on interagency coordination within the Denver Region. Chapter 9 includes personal discussions with several agencies involved in planning, development, and emergency response in the Denver Region. Finally, Chapter 10 presents conclusions, limitations of the study, and recommendations for further research.

Chapter 2

Case Studies

2.1 Importance of Case Studies

The study of past events lends many valuable suggestions on how to ameliorate the damaging results of an unexpected event. Awareness of unknown weaknesses in a system is discovered after damaging events. Each hazardous event can be dissected and analyzed to find ways to either reduce or prevent the same outcome in the future. However, there are so many unknowns, especially due to the growing physical and social complexity of our societies, which it is impossible to build infrastructure systems that will withstand any stressor or deflect every terrorist attack attempt. Even though protecting the entire infrastructure system and all human lives from a hazardous event is unrealistic, it is still vitally important to take the lessons learned from past cases and apply that to future planning and mitigation. The following case studies shed great light on how a single incident can affect multiple systems, from transportation systems to water systems to fiber optics systems. Interdependency between individual systems, especially during extreme events, must be understood in order to progress with more reliable and resilient infrastructures. A great deal of this understanding can come from examining past cases. In this chapter three important U.S. disasters will be discussed: the 2001 Baltimore tunnel collapse, the 2005 impact on New Orleans of Hurricane Katrina, and the 2003 North American Blackout.

2.2 Baltimore Tunnel Collapse (2001)

Tunnels are critical structures in the transportation systems, becoming increasingly susceptible to various hazards. Several recent tunnel related disasters include the Gotthard tunnel in Switzerland in 2001, the Mont Blanc tunnel from France to Italy in 1999, and the Channel Tunnel in from Great Britain to France in 1996 (Rosmuller and van den Brand 2003). In the Gotthard tunnel, two trucks collided head-on filling the world's second longest tunnel with fire, killing 11 people, and shutting down the tunnel for months, affecting the economy greatly (figure 2.1) (Miller 2001). The Mont Blanc tunnel disaster started from a refrigerated trailer catching on fire, one that took fifty hours to completely extinguish, killing 39 people (Bailey). Appendix A shows the inside of the improved Mont Blanc tunnel with safety features after reopening three years after the fire. In the case of the Channel Tunnel, again the incident was fire related when a shuttle train carrying heavy goods erupted in flames. The Channel Tunnel consists of three parallel tunnels; a service tunnel and two railway tunnels set 98 feet (30 meters) apart. This particular case shows the value of having parallel tunnels for evacuation and repair purposes (Kirkland 2002). These three specific incidents along with others are triggering the need for tunnel safety improvements.

Figure 2.1: Fire in Gotthard Tunnel (photo from BBC News http://news.bbc.co.uk/2/hi/europe/1723406.stm)

Trains carrying everything from people to supplies including hazardous materials are guided through tunnels which are now becoming key targets to terrorists. Several bombings have been directed at tunnels such as the 2005 London Bombings that caught the media’s attention. In 2006, police arrested Assem Hammoud from Lebanon, who confessed to plotting an attack on the New York City tunnels. The plan was to attack the trains under the Hudson River in efforts to flood lower Manhattan (McNamara 2006). Attacking a tunnel in a major city is comparable to severing one of its main arteries. Lives will be lost, shipments delayed, and the transportation system potentially paralyzed, depending on the location and importance of the tunnel’s location. Terrorist attacks are not the only concern to tunnels. Other issues can arise that are not deliberate but instead indirect, such as a derailment as in the case of the 2001 Baltimore tunnel collapse.

On July 18, 2001, an eastbound CSX freight train derailed 11 out of 60 cars when passing through the Howard Street Tunnel in Baltimore, Maryland. Nine cars carried hazardous materials including: hydrochloric acid, glacial acetic acid, hydrofluoric acid, propylene glycol, tripropylene, and ethyl hexyl phthalate. One tank car released more than 28,600 gallons of tripropylene (National Transportation Safety Board 2004). In addition, several of the freight cars were carrying wood pulp and large rolls of paper, both highly combustible. Although the cause is unknown, the derailment ultimately resulted in a fire reaching almost 1,500 degrees Fahrenheit. The train halted approximately a half mile from the north end of the tunnel, and at this time the engineer attempted to contact a CSX Transportation dispatcher by radio, but was unsuccessful with the antenna unable to transmit within the tunnel. The engineer was able to use his cell phone to contact a dispatch center in Florida, at 3:15 p.m. The public started to see a heavy black cloud come from the tunnels through the manholes at 4:00 p.m., and finally at 4:04, the train crew contacted the CSX Transportation dispatcher in Jacksonville and Baltimore's 911 Center. The time difference between the CSX Transportation notifying the Baltimore Fire Department of the incident was over an hour, showing a weakness in the communication system, resulting in a delayed response to the location of the incident at 4:18 p.m. (Styron 2001).

Although the communication link between the engineers in the tunnel and the Baltimore City Fire Department failed, the City of Baltimore's consolidated Communications Center proved to be tremendously successful. "The Incident Commander believed that communications and radio capability of the BFD were the most important features of the incident's success. The second success factor was the interagency cooperation" (Styron 2001). A centralized communication center allows for a more organized and efficient means of coordinating all the response teams to maximize their potential in aiding in the aftermath of a disaster. Some of the key features of the Baltimore City Fire Department include:

- Mapping display of emergency locations
- System redundancy to ensure maximum reliability
- Single call for service to generate multi-agency response

- Inter-agency communications at major emergencies
- Automated service calls for better tracking and follow-up
- Shared resources, information, facilities, equipment, and costs
- Enhanced coverage in buildings, tunnels, and all areas of the city
- Emergency button for life threatening situations
- Automatic Vehicle Locators on Medic Units

List provided by Styron (2001)

The Baltimore City Fire Department was joined by several city, state, and federal agencies, each working together in the response to the incident. These agencies include: Baltimore City Police Department, Baltimore Department of Public Works, Baltimore City Emergency Management, CSX Transportation, Baltimore County Fire Department, Maryland Department of the Environment, National Transportation Safety Board, United States Coast Guard, and representatives from the South Baltimore Industrial Mutual Aid Plan. Each of these groups has individual expertise that can only be sued to its fullest capacity if strong coordination is performed. In the case of the 2001 Baltimore tunnel, great success resulted from the above groups directly cooperating and coordinating with one another.

Although significant interagency coordination was successfully performed, coordination between the incident and the public was lacking. A public information officer was not designated during the initial stages of the event, limiting access of information to the public. Several media accounts were vague and incorrect, promoting public confusion and frustration. The need for establishing a public information sector with a public information officer is essential and must be set prior to major events. The public relies greatly on the media to inform with accurate information.

The hazardous materials transported on the derailed train brought focus to the issue on transporting such materials through the city where a large percentage of the population is exposed. Five-thousand gallons of hydrochloric acid was spilled, along with other combustibles. Each day, an average of 40 freight trains runs through Baltimore (Styron 2001). The public must be aware of these facts, and local emergency planning committees need to coordinate among several agencies to develop a mitigation plan to address this vulnerability.

Baltimore's Mayor testified on the vulnerability of the City of Baltimore on October 5, 2001 stating, "One of the first things we realized- based on our experience in the CSX tunnel fire-was that most rail yards and tracks, filled with chemical tanker and munitions cars, represent one of our most vulnerable targets" (Styron 2001). Understanding where a city is most vulnerable is the first step toward reducing this vulnerability. One of the many lessons learned from the Baltimore tunnel accident focuses on fully developed emergency preparedness plans. "Emergency preparedness documents compiled by the Baltimore Office of Disaster Control and Civil Defense that were reviewed by Safety Board investigators do not contain information on hazardous materials discharge response procedures specific to tunnel environments or infrastructure information on the Howard Street Tunnel" (NTSB 2004). Having this information on hand is essential for a successful emergency response. A specific plan for every type of circumstance, including tunnel accidents regarding hazardous materials, is critical but often ignored.

The entire Baltimore area took a hit from this incident, especially the transportation system. Any traffic coming from the downtown area was redirected away from any potentially hazardous areas. Highways heading into the city were also closed, changing all the traffic routes. These redirections resulted in a gridlocked system for cars, buses, and the light rail. Several trains initially scheduled to run through the tunnel under Howard Street had to be redirected, causing shipping delays, some up to two weeks. If another incident were to occur simultaneously, the city would not be able to act appropriately with a paralyzed transportation system. Resources could not be allocated, emergency personnel would find immense difficulty reaching the location of another incident, and the number of casualties could have increased due to the elevated number of people within in an area simply due to traffic congestion.

The water system was also significantly affected by the rupturing of a 40-inch diameter water main located directly above the tunnel, (see figure 2.2). One block east of the cast iron water main failure, a 40-inch valve was closed along with another valve to an interconnected 20-inch diameter water line. This helped isolate the damaged area; however 14 million gallons of water were lost during the time between the water main break and when the supply was completely shut off (NTSB 2004). The flooding resulted in several negative effects including the collapse of numerous city streets, reducing the ability to extinguish the fire, taking out electricity for 1,200 users, and damaging several adjacent buildings. In addition to the water escaping from the damaged water main, the Department of Public Works stated that approximately 60 million gallons were being used solely to suppress the fire. This high volume request forced the Water Department to re-route several pipe channels to make sure water was being serviced to the nearby hospital and other buildings (Styron 2001).

Figure 2.2: Ruptured 40-inch water main (*The Baltimore Sun 2001*)

Further adding to the complexity of the situation, the "fire caused major Internet slowdowns in the Middle Atlantic States, and delays rippled across the country as companies diverted Web traffic to other cables. Fiber-optic cable running through the tunnel was damaged by the fire" (NYT 2001). Fiber optics is important for emergency communication and other applications. Silicon Valley company tracked the Internet traffic saying that this tunnel incident caused the "worst congestion in cyberspace in the three years that it has monitored such data" (Styron 2001).

The 2001 Baltimore Tunnel Collapse is an incident that each and every city should learn from in terms of systems planning, as well as coordination and preparedness. The derailment of the freight train affected the transportation, water, and communication systems simultaneously, displaying vulnerability in the heart of Baltimore. The City of Baltimore and CSX Transportation suffered economically in the magnitude of $12 million (NTSB 2004). Even the economic loss due to the delay of the Baltimore Orioles baseball team for four games was $4.5 million (Styron 2001). Unfortunately incidents all together cannot be avoided, but there are several measures that can be taken to lessen the severity.

Location of major transportation arteries, such as the Baltimore tunnel, close to buildings creates vulnerability. The rail tunnel runs underneath several downtown landmarks, the Maryland General Hospital, and many other important locations. These vulnerable locations need to be addressed. Developing backup supply systems is one way of minimizing the magnitude of physical and economic damage. Several infrastructure systems are centralized promoting extensive vulnerability if an incident were to occur at these locations. In the case of the 2001 Baltimore tunnel collapse, the water, transportation, communication and electrical systems were all affected by the derailment of the train. If these systems were separated, the repercussions of this incident could have been substantially reduced. Where these systems are already coupled, alternative ways of maintaining each individual system must be considered.

2.3 Hurricane Katrina (2005)

Hurricane Katrina brought much of the Gulf Coast to a devastating halt. Millions of people were affected, all major economic operations in the affected area were ceased, and social unrest became a heartbreaking reality. One-hundred and forty-five mile per hour winds produced by this category three storm sent a twenty-nine foot high water surge ashore (NYT 2010). The levees in New Orleans were discovered to be incapable of handling these forces from the water surge, causing them to fail. "An exodus of hundreds of thousands left the city, many becoming refugees, finding shelter with nearby relatives or restarting their lives in states as far away as Massachusetts and Utah" (NYT 2010). A series of poor planning and inadequate emergency response resulted in a disaster elevated by human error.

Hurricane Katrina exposed the high vulnerability levels that exist within the United States. A total of 1,330 deaths were recorded, reaching four times as many from when Hurricane Andrew hit in 1992. Additionally, Hurricane Katrina caused more economic damage than any previous U.S. natural disaster. Housing damage equated to $67 billion, loss of consumer durable goods $7 billion, damaged business property $20 billion, and government property another $3 billion, totaling $96 billion in estimated damage (U.S. Executive Office of the President 2006).

In a letter addressed to the President of the United States, on February 23, 2006, Frances Fragos Townsend, Assistant to the President for Homeland Security and Counterterrorism, stated:

> *"Despite all we do, however, Hurricane Katrina was a deadly reminder that we can and must do better, and we will. This is the first and foremost lesson we learned from the death and devastation caused by our country's most destructive natural disaster: No matter how prepared we think we are, we must work every day to improve"* (U.S. Executive Office of the President 2006).

These words are directly addressed to engineers, planners, government officials, and even residents. Each person has a role as part of the greater whole in developing a resilient community to face hazards of varying forms. The levees in New Orleans are a specific example of undercared for engineering responsibility. At the location where the CSX Railroad crosses the north arm of the Industrial Canal (in the eastern part of Orleans Parish), metal gates previously were placed for use in case of an emergency. A train derailment damaged these gates, and engineers opted for the use of sandbags to "seal the levee 'I' walls where the railroad passed through the walls" (NOVA 2005). When the storm surge caused by Hurricane Katrina reached these walls, breaks formed between the sandbags, allowing water to rush through into the city. In addition, the levees in front of the Mississippi River-Gulf Outlet had deteriorated over time. These levees comprise the eastern portion of the “ring” of levees encompassing St. Bernard Parish and the Lower Ninth Ward, and were intended to provide protection from hurricanes. Additional levees running along Gulf Intracoastal Waterway failed, causing more flooding. The floodwaters then eroded the “earthen levee embankments”, ultimately resulting in weakening of the soil foundation, causing the levee to breach (NOVA 2005). Furthermore, a chain reaction of levees continued to fail, leaving New Orleans submerged in water. The flooding handicapped New Orleans’ entire infrastructure system.

In the paper, “Disoriented City: Infrastructure, Social Order, and the Police Response to Hurricane Katrina”, the author Benjamin Sims investigates how dense concentrations of infrastructure coincide with highly structured social institutions. Even parts of a city that are not directly involved in the planning and maintenance of some infrastructure systems are affected by them. These systems tend to be overseen by a complicated network of bureaucracies, many limited by specific political and geographical boundaries (Graham 2010). New Orleans is a perfect example of how societies have become highly dependent on infrastructure systems, especially as population growth throughout the United States continues.

Nearly everybody who resides in a developed community has become highly dependent on electricity, fresh water supply, waste water disposal, communication through either telephones or wireless connections, and transportation. In New Orleans on August 29, 2005, the electrical system, including towers used for emergency response radio systems were all shut down due to the ferocity of the storm. Even the telephone systems (hard-wired and wireless) were affected, leaving three million phone lines disabled and 1,477 cell towers out of service. Radio and television stations were also “knocked off the air”, leaving the communications systems in a state of paralysis. Paul McHale, (the Assistant Secretary for Defense for Homeland Defense) stated, “The magnitude of the storm was such that the local communication system wasn’t simply degraded; it was, at least for a period of time, destroyed” (U.S. Executive Office of the President 2006).

Performance levels of highway bridges in Mississippi, Louisiana, and Alabama, and moveable bridges in the Gulf Coast were observed under the intense environmental conditions caused by the hurricane. The bridges that received the most damage were those adjacent to water, as opposed to those that spanned railroads and highways. Below, figure 2.3 shows the approximate repair costs for the bridges in each of the three states. Data are from ASCE, “Hurricane Katrina: Performance of Transportation Systems” Monogram 29, August 2006 (DesRoches 2006)

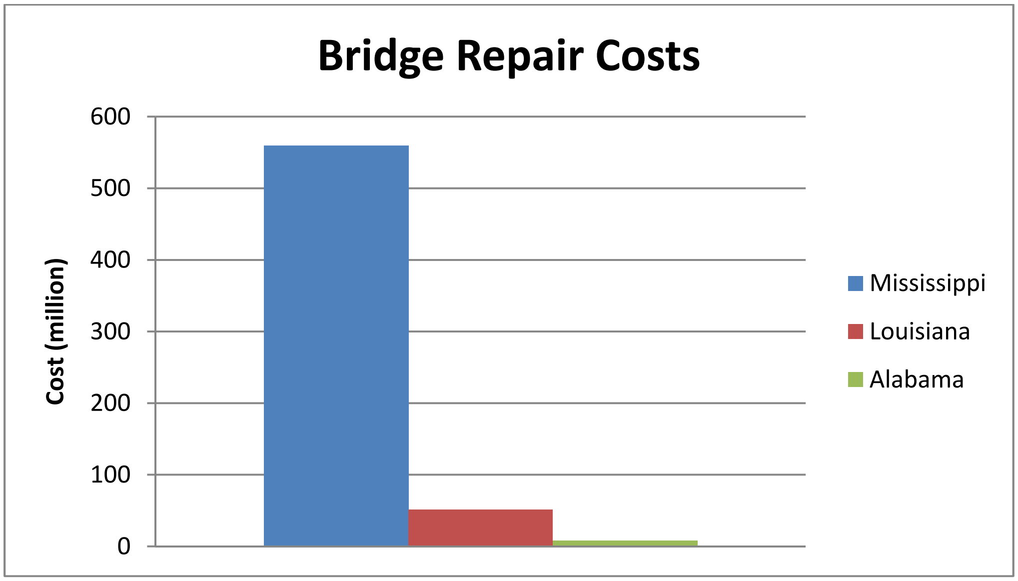


Figure 2.3: 2006 Estimated bridge repair costs resulting from Hurricane Katrina

Although Mississippi experienced the most repair costs, the number of damaged bridges in Louisiana exceeded those of Mississippi and Alabama combined, with thirty-two bridges (Mississippi with seven and Alabama with four). Some of the key bridges affecting the infrastructure system are as follows:

- **US90 Henderson Point Bridges (Mississippi)** - These were two parallel bridges running over the CSX railroad. US90 route and CSX railroad were both closed at this location.

- **Biloxi-Ocean Springs Bridge (US90) (Mississippi)** – A four lane, 1.6 mile long bridge providing access between two cities over the Biloxi Bay. Several spans were unseated by the twenty-foot storm surge, closing the entire bridge, eliminating the use of a major passageway. The estimated replacement costs were $275 million.
- **Biloxi Back Bay Bridge (Mississippi)** – This bridge became the only route to Biloxi after the hurricane, acting as a "critical route for the recovery efforts in Biloxi". Three of the four lanes remained open.
- **Bay St. Louis Bridge (US90) (Mississippi) –** Connected Hancock and Harrison counties. Majority of the decks were unseated. Bridge was immediately closed following the hurricane. Estimated repair costs were $267 million.
- **I-10 Twin Spans (Louisiana)** – Two separate spans, each 5.4 miles long,, directing traffic between St. Tammany and Orleans parishes. This bridge held great "importance as a major transportation link".
- **Cochrane-Africatown USA Bridge (Alabama)** – This bridge carries U.S. 90 above a port, railroad tracks, and the Mobile River. The hurricane pushed a 13,000-ton oil drilling platform into the bridge, which was currently being refitted at a nearby repair facility.

(DesRoches 2006)

The failure of several important bridges forced traffic to alternative routes. For example, truck traffic was rerouted to highway I-12 after the bridge crossing over Lake Pontchartrain (which carried highway I-10). Some railroad routes, not directly connecting to New Orleans, were also rerouted through Memphis and other Midwest railways. The ability to reroute portions of the transportation system demonstrates the effectiveness of redundancy in situations similar to Hurricane Katrina (USGCRP 2008).

Moveable bridges in the Gulf Coast account for a majority of the marine and vehicular traffic in Louisiana. The damage to these moveable bridges “complicated travel routes for both modes of transportation. In many cases, water inundation destroyed lift motors and electrical systems, rendering structurally sound bridges immovable. Due to the importance of shipping to the region and marine transport of relief goods for disaster recovery, bridges with damaged mechanical components were often forced open to allow marine traffic to pass” (DesRoches 2006). This example demonstrates the reliance upon electricity among specific bridges, which in turn initially impeded relief efforts.

Several of the damaged roadway and railroad bridges along with damage caused by debris, subsequently affected the usability of numerous railroad tracks. Six of the seven main freight railroads were prevented from entering Louisiana, Mississippi, and Alabama (DesRoches 2006). The transportation routes used to bring fuel to the affected areas were paralyzed. The lack of fuel prevented using backup generators. A specific example of this cascading effect, from the failure of the transportation system to the failure of an electrical system, focuses on an individual business (amongst many others) being forced to evacuate their offices simply due to a shortage in power supply. CII Carbon (a leading producer of calcined petroleum coke), initially continued working at the corporate office in New Orleans, utilizing the backup generator. The generator proved to be beneficial until 12 hours later when the gasoline supply was used in its entirety. Batteries were the succeeding line of energy, but quickly drained, forcing the employees to relocate to other offices (eNSYNC Solutions 2011). This example is amongst thousands during Hurricane Katrina, demonstrating the strict dependency society has on energy supply, which in turn depends on the transportation or other infrastructure system.

Areas not directly experiencing significant damage due the hurricane itself suffered similar consequence losses due to the drastic fuel supply decrease. Crude oil and refined petroleum product supplies were disengaged by the loss of electricity supporting the pump stations for three major transmission pipelines (the Colonial, Plantation, and Capline Pipelines). Refined product lines running to the southern and eastern states ceased, as well as gasoline and diesel supply to the Midwest. “About 1.4

million barrels per day of the crude oil supply were lost, accounting for 90 percent of the production in the Gulf of Mexico. Nearly 160 million liters per day of gasoline production was lost, accounting for 10 percent of the U.S. supply" (O'Rourke 2007).

In addition, running water and sewers became unusable (Graham 2010). For example, in "less than 48 hours after Katrina made landfall, the Mississippi Department of Health issued a blanket boil water notice for all public water systems in the State's six most impacted counties, located in the coastal region…A boil water notice alerts the public and informs them to boil their water to prevent health impacts from drinking water potentially contaminated with bacteria" (Hatfield et al. 2006). Another high concern related to water treatment included the damage to several wastewater treatment facilities, resulting in public exposure to raw sewage (Hatfield et al. 2006). The floodwaters contaminated by this raw sewage increased the susceptibility to infectious disease.

A major issue realized by this situation of chaos and destruction was that "individual local and State plans, as well as relatively new plans created by the Federal government since the terrorist attacks on September 11, 2001, failed to adequately account for widespread or simultaneous catastrophes" (U.S. Executive Office of the President 2006). National preparedness for any event, whether originated by nature or man, is a continuing problem to the United States. Efforts must be made to improve the nation's awareness and capabilities in preventing the same magnitude of damage caused by past natural disasters such as Hurricane Katrina.

A primary lesson learned from this 2005 hurricane is the vulnerability of emergency response in such a catastrophic event of this magnitude. Important buildings vital in an emergency response operation were flooded, including hospitals and police stations. Backup generators were also disabled after being flooded, resulting in the loss of radio tower capabilities. And even for those generators that were intact, the devastation to transportation systems prevented the timely delivery of replacement fuel. Emergency communications were disconnected, making any strategic planning (e.g., mobilizing, and distributing supplies) highly difficult (Graham 2010). The lack of communication capabilities coupled with a flooded transportation system became a recipe for mass devastation.

Disaster is not induced solely by an individual stressor, whether natural, man-made or intentional, but also by the degree of complexity of the system toward which the stressor is applied. A category three hurricane is not considered a disaster until it reaches civilization, taking lives and generating physical damage. Most infrastructure systems in the United States are highly dependent on one another, necessitating a focus on means of reducing potential damage from a likely disaster. Some of these means include: decoupling individual infrastructure systems, making them less dependent on one another; developing plans for alternative energy, transportation routes, backup water supply etc.; and ensuring that governmental agencies are highly organized so that all levels are fully operable at the time of a hazardous event. An example of poor planning of the New Orleans emergency response team was that all police officers were forced by law to reside in the city limits. At the time of the hurricane, nine-hundred out of fourteen-hundred officers were homeless, forcing them to fend for themselves. In this situation, the officers had to focus on self-survival, preventing them from being able to help New Orleans citizens (Graham 2010). How can an emergency team respond when the response team itself is trying to save their own lives? Unfortunately, the following quote describes the opposite of what occurred in New Orleans in August 2005:

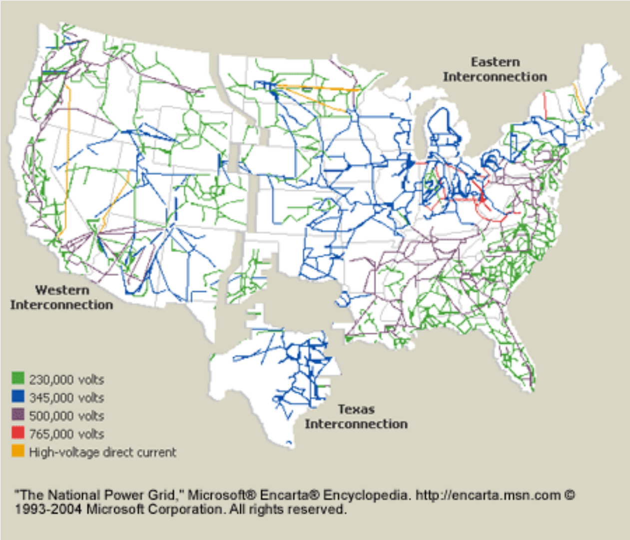
> *"Basic federal law and practice have never abandoned the principle that initial responsibility rests with first responders and local management, we also demonstrate the importance of the relationship between all levels of government, nongovernmental organizations, and the general public, and how planning and support at the federal level should fan out through the intergovernmental system"* (McGuire and Schneck 2010).

These words preach the necessity of having an organized system at all levels of representation. Focusing solely on the design of a more robust or resilient infrastructure system is critical, but does not encompass the entire picture on how a system truly operates. It takes the people within the system to become aware of how to handle any given situation, whether anticipated or completely unexpected. Hurricane Katrina is a prime example of the needed marriage between organization and communication along with sustainable development.

2.4 North American Blackout (2003)

Today the electric power grid has transformed from over 4,000 individual electric utilities, into an interconnected system. These individual utilities were low-voltage connections from power plants that distributed electricity to nearby customers. After World War II, the demand increased significantly, pushing the electric utilities to interconnect their transmission systems. By joining, they were able to meet the demands and produce electricity at a much lower cost. Naturally the demand continued to rise and the system had to increase, leading to more lines and higher-voltage interconnections to be able to reach longer distances supporting millions of customers (eia 2009). The U.S. electric sector has developed into a highly notable achievement.

The electric power grid is one of man’s greatest feats, but also one of man’s greatest vulnerabilities. In this day and age all are dependent on electricity to power their lives, yet in a matter of seconds, power lines once running to millions of people could be severed and no longer transmitting electricity. This affects power plants, emergency operations, communication, business, homes, and more. There are three power plant grids in the United States supporting the contiguous states: the Eastern Interconnected System, the Western Interconnected System, and the Texas Interconnected System (all shown in figure 2.4) (eia 2009). Each grid system is highly interdependent, making it highly susceptible to a domino effect such as the 2003 North American Blackout.



"The National Power Grid," Microsoft® Encarta® Encyclopedia. http://encarta.msn.com © 1993-2004 Microsoft Corporation. All rights reserved.

Figure 2.4: The National Power Grid (from Microsoft Encarta Encyclopedia, http://encarta.msn.com)

On August 14, 2003, in the heat of the summer, energy consumers were running their air conditioners at increased levels, demanding more from the energy grid. At 1:00 p.m. EDT, the grid operators at First Energy (a regional utility), requested the power plants for more volts to meet the increasing demand. An operator at the power station on the shore of Lake Erie responded by pushing to maximum capacity. Five minutes later, the power station crashed, forcing electricity from other areas to make up for the drop in supply. Had this power station crash been the only issue, the power grid would have continued to operate more or less normally and without interruption. However, the electrical grid is not designed to accommodate several unexpected incidents. At 3:05 p.m., an untrimmed tree shorted out a 345-kilovolt transmission line near the town of Walton Hills, Ohio. That small instance redirected electricity to other lines causing them to overload and overheat, ultimately short-circuiting. The cascading effect resulted in an alarm system failing, preventing the First Energy operators from responding to the situation at hand. At 4:06 p.m. another line failure overloaded the system pushing the effects to the East Coast and causing 265 power plants to shut down, affecting 50 million people in eight different states (New York, Massachusetts, Vermont, Connecticut, Ohio, Michigan, Pennsylvania, and

New Jersey) as well as in Ontario (Achenbach 2010). This is equivalent to the entire population of France or Great Britain (Economist 2003).

Figure 2.5: 2003 North American Blackout (from Skywatch Media)

The combination of consumer demand and a single shortage resulted in a widespread power outage affecting millions of people, and was a wake-up call in reorganizing the electricity sector, making it less interdependent within itself as well as with the transportation, water, and communication systems. As a result of the power outages, air and ground transportation systems were shut down, drinking water systems as well as sewage processing plants ceased operations, manufacturing plants halted, and several emergency communications systems were rendered inoperable (GAO 2003). Parts of the transportation system directly affected by the power outage including airports located in Toronto, Newark, New York, Detroit, Cleveland, Montreal, Ottawa, Islip, Syracuse, Buffalo, Rochester, Erie, and Hamilton (ELCON 2004). Traffic signals failed, causing New York City to become completely gridlocked. Thousands of people were trapped in lifts, subway trains and other places. Many of these individuals spent the nights in parks and plazas. Even crime rates increased with the absence of street lights and alarms (Economist 2003).

In addition to the transportation system facing the repercussions of the electrical system failure, the energy sector also faced numerous consequences. One case included eight oil refineries in the U.S. and Canada that were affected, threatening a gasoline shortage in the Detroit Metropolitan Area that would cause an energy emergency. The Governor of Michigan in fact issued two Declarations of Energy Emergency on August 22, 2003 which suspended certain air quality regulations that could potentially lead toward a gasoline shortage (ELCON 2004). Also, pipelines were adversely affected, such as one of the main pipeline networks operated by Enbridge Inc. for Canadian oil shipments to the U.S. Midwest and southern Ontario. "Much of the two million bpd [barrels per day] system, the world's longest for crude oil and petroleum product shipments, was shut down east of Lake Superior. Enbridge reported that it was forced to cut volumes moving to its terminal in Superior, Wisconsin, from Alberta to prevent overfilling storage tanks" (ELCON 2004).

Negative effects on the fuel supply directly tied into communication failures, such as telephone lines, further adding to the cascading downfall effect. The local telephone systems used standby generators, which required fuel. Several government offices and private entities operated generators as well to maintain a power supply at their individual sites. The competition for a limited fuel supply heightened, and suppliers found difficulty meeting this demand due to the inability to pump fuel from underground storage tanks without their own power or generators (Lark 2003).

Integration between infrastructure systems has become increasingly complicated, even cyber systems were affected by the power outage not because of the electricity shortage directly connected to the computers, but due to the inability to run air conditioning units . At the time of the incident, any large-scale system operated using Uninterrupted Power Supply (UPS) units. These systems likely allowed the system to properly reboot once power was resumed. During the time of this blackout, however, ambient temperatures were high, requiring cooling in the server rooms. Air conditioning systems were inoperable without back up generation, making it impossible to maintain many communication systems (Lark 2003).

Physical damage coinciding with extensive economic damage cost all the affected areas millions of dollars or more. Anderson Economic Group performed an estimate for the total impact on US workers, consumers, and taxpayers due to the blackout, concluding it to be about $6.4 billion. Approximately $4.2 billion was lost income to workers and investors, another $1 to $2 billion lost to utilities affected, and between $380 and $940 million in costs due to lost commodities such as frozen goods and produce. Another $15 to $100 million lost in additional costs to government agencies resulting from overtime and emergency services (Anderson 2003).

Each of the eight affected states as well as Ontario became handicapped, providing an alarming opportunity for a potential attack. If an intentional attack were to occur in any of the locations affected by the power outages, several defense mechanisms would be inoperable. Refineries and gas stations would not be available, leaving many without fuel. Emergency efforts rely heavily on the electrical system for support. Whenever there is an emergency, people have been programmed to immediately dial 911, yet in the 2003 blackout, cellular networks were interrupted as well as 911 communications. Making sure resources are available during a hazardous event is a critical step that must be taken to ensure local and national security. If a single tree leads to a cascading power outage of this extent, imagine what a planned terrorist attack could do.

The necessity of having the ability to monitor and control system failures is a definite lesson learned from this accident. A formal means must be established to notify control room personnel immediately when functions critical to the system's reliability have failed. Failure of the alarm system has pushed the need for an automated method to alert power system operators when the power system status indications are not current or when the alarms are not being received. Additionally, the backup capacities have in the past not been well known. Knowing which backup capabilities are available to be utilized in instances such as the blackout, can allow operations to continue. All critical communication systems and computers must have a backup power supply, and one that is periodically tested (NERC 2003).

A fine balance between supply and demand is a continuous challenge for the electric sector, both locally and regionally. Electricity is consumed at nearly the same time as it is produced because large quantities of energy cannot effectively be stored, allowing a change in one area of the grid to instantaneously affect another area (eia 2009). Furthermore, congestion is a growing problem in the transmission system. The blackout incident in addition to current growth related issues in the electric sector have pushed the need for reforming the grid system, leading to the federal government allocating funds to these efforts. The economic-stimulus package is providing $4.5 billion to smart grid projects with an additional $6 billion towards new transmission lines (Achenbach 2010). Smart grid efforts are in place and emphasize the need for demand management to reduce the level of vulnerability that looms over the system.

Although efforts are taking place to better the system, the electrical sector is difficult to restructure due to its high complexity with thousands of interconnected transmission lines, as well as in terms of regulatory oversight by the government. Several challenges the electric grid infrastructure faces, provided by the U.S. Energy Information Administration, are as follows:

- Sitting new transmission lines (and obtaining approval of the new route and needed land) when there is local opposition to construction.
- Determining an equitable approach for recovering the construction costs of a transmission line being built within one state when the new line provides economic and system operation benefits to out-of-state customers.
- Ensuring that the network of long-distance transmission lines reaches renewable sites where high-quality renewable resources are located, which are often distant from areas where demand for electricity is concentrated.
- Addressing the uncertainty in Federal regulatory procedures regarding who is responsible for paying for new transmission lines; this uncertainty affects the private sector’s ability to raise money to build them. (eia 2009)

A primary issue in preventing protection amongst critical infrastructure systems is that "security measures have been added after the infrastructure is in place, which is costly and creates potential conflicts between security and efficiency" (GAO 2003). Integrating these security measures in the pre-construction stages would prove to be most optimal for potential future hazardous events. Upfront costs and time, however, often prevent such measures from being taken. Specifically with the electricity sector, concerns have been raised about the "increasing reliance on information and control systems, which are potentially vulnerable to cyber attack…" (GAO 2003). After the 2003 blackout accident occurred, former Secretary of Energy in the Clinton Administration, Governor Bill Richardson of New Mexico stated that, "We are a major superpower with a third-world electrical grid. Our grid is antiquated. It needs serious modernization" (Luke 2010). This modernization not only needs to be focused on transmission capacity, but also with how the electric sector is integrated with other infrastructure systems.

Issues amongst the energy sector translate into issues amongst other sectors, including the transportation, water and communication sectors. Unfortunately poor regulation of the energy market was one of the primary causes of the 2003 blackout. "Industry watchers say that since the power-transmission business is so tightly regulated, companies do not have enough incentive in beefing up the network" (Economist 2003). Whether improvements come from within the industry or are driven by governing powers, radical improvement of the electric grid is a glaring need that the United States must face.

Risk assessments can be used to bring the awareness of the level of criticality of the interconnectedness between infrastructure systems. As a starting point in forming progress to reduce vulnerability levels, federal state and local agencies need to develop the ability to assess the risk associated with these interdependencies as they exist within each community and being able to quantify the subsequent repercussions. The next section discusses current methodologies being developed to assess risk.

Chapter 3

Methodologies of Assessing Risk

3.1 Background

Risk is defined as the product of probability of a stressor by the level of vulnerability by the consequence. Vulnerability is defined as the estimated susceptibility of a population or area to a particular stressor. Consequence is defined as the amount of harm caused by a stressor. For example, if the probability of a snow storm at a particular location in Arizona, USA, then the risk would be zero even though the population at this location would be more vulnerable to a snow storm than a population in Colorado because they are not adapted to behaving under the conditions of a snow storm. Assessing risk refers to the process in which data is collected and analyzed to determine the probability of a stressor, the vulnerability, and the magnitude of consequence used in calculating risk. Challenges exist in measuring risk for several reasons: definitions of risk vary, risk is composed by an infinite number of independent variables and therefore difficult to quantify, and several direct and indirect variables are simply unknown. In efforts to understand and estimate risk levels, numerous researchers have developed models and methodologies to reduce the number of unknowns and approximate risk in interdependent infrastructure systems from a local level to a national level. Three of these methods in assessing risk are presented below:

3.2 Hierarchical Holographic Modeling

Hierarchal Holographic Modeling (HHM), developed by Yacov Haimes, is "a holistic philosophy aimed at capturing the diverse characteristics of a system – its multiple perspectives and hierarchies. The term holographic refers to having a multi-view image of a system to identify vulnerabilities" (Haimes, Santos & Williams 2005). This method is well suited to bi-direction interdependency relationships. For example, for a transportation system one may evaluate disruptions in the system with their consequent effects on external sectors, as well as the effects placed onto the transportation system as a result of a change in the industry sectors' travel demands. The perspectives resulting from the HHM make the cascading effects between infrastructure interdependencies more apparent. However, one of the issues that arise from HHM is the vast amount of possible risk scenarios. A method called Risk Filtering, Ranking, and Management (RFRM) previously developed by Haimes and colleagues addresses this issue of information overload. This method was designed to "identify, prioritize, and manage risks to complex, large-scale systems". RFRM extracts information from HHM, highlighting the more critical areas and allowing decision makers to place their attention there. The RFRM can help "distinguish priority treatments for risk issues with high frequency of occurrence but with relatively low consequences, versus those with low likelihood but with catastrophic consequences" (Haimes et al 2005).

Haimes et al (2005) demonstrate the use of Hierarchical Holographic Modeling in determining the interdependencies of transportation systems. Initially the transportation interdependencies are categorized under six "head topics": Emergency Response and Recovery (ERR) Jurisdiction, Intermodal, Physical, Economic, Function and Users. Additions to these topics based on specific cases are not prohibited, making this type of modeling more versatile. The six main topics are then extended into individual categories identifying the interdependencies associated with the transportation system.

Data provided by numerous sources are then associated with the subcategories. The collected inventory helps the state departments of transportation determine the critical assets as well as identify other sectors dependent on the support of the transportation system. Based on set parameters, such as proximity, economic areas and traffic volume, the interdependencies are ranked by usage level. The identified interdependencies from the analysis are cataloged for use of identifying the assets within a particular US region. Table 3.1 below depicts sample inventories and parameters extending from four of the six main topics:

Table 3.1: Sample inventory and parameters for different interdependency categories

Category	Inventory	Parameters for Prioritization
Jurisdiction	Agencies Districts	Role or nature of support, delay caused
Intermodal	Highways	Average Daily Traffic (ADT),

	Airports Rail Stations (passenger and freight) Transit	Average Daily Truck Traffic (ADTT), detour, road classification, revenue, #passengers, freight volume, special value
Economic	Industrial parks and export zones Top companies Top export commodities	Revenue, special value/criticality to nation/state
Users	Military installations Hospitals	Proximity, power projection platform (PPP) or power support platform (PSP) proximity, level classification

(Table from "Assessing and Managing the Inoperability of Transportation Systems and Interdependent Sectors", by Haimes, Santos and Williams)

Using the Hierarchical Holographic Modeling, "two sets of priorities are generated: (1) critical sectors affected by transportation disruptions (e.g., businesses, retail trade, recreation), and (2) critical sectors that impact the operations of the transportation system (e.g., sectors dealing with transport of hazardous materials)" (Haimes, Santos & Williams 2005). Once the critical sectors are identified, more specific analysis should be performed to understand the impacts from various stressors (e.g., natural disasters, man-made hazards, or intentional attacks), and future actions should be implemented to reduce the identified risk.

3.3 Optimization Based Methodology

Optimization based methodology stems from the main concern of the incapability of reaching victims in need of assistance in the case of an emergency. "The optimization is clearly conditioned on the availability of support infrastructure (e.g., transportation network) and socioeconomic aspects" (Buriticá, Gómez , Sánchez-Silva and Dueñas-Osorio 2011). The optimization based methodology creates a framework for resource allocation by creating a hierarchical structure in which clustering algorithms are extracted. The hierarchical structure is constructed using a *systems approach*, allowing one to gain "conceptual insight into the problem and reduce the computational cost of finding the solution" (Buriticá et al 2011). Similar to the Hierarchical Holographic Modeling previously discussed, the structure of the hierarchy starts general and transcends into more detailed descriptions at the bottom of the tree formation.

Each level within the tree-formed flow chart represents a level of the hierarchy, which can be analyzed individually to solve a simplified network. The key to this method is "successive clustering", simply extracting information from the grand scheme to obtain valuable information and develop solutions. Figure 3.1 below shows the extraction of fictitious networks from the hierarchical representation that encapsulates the system's intrinsic behavior.

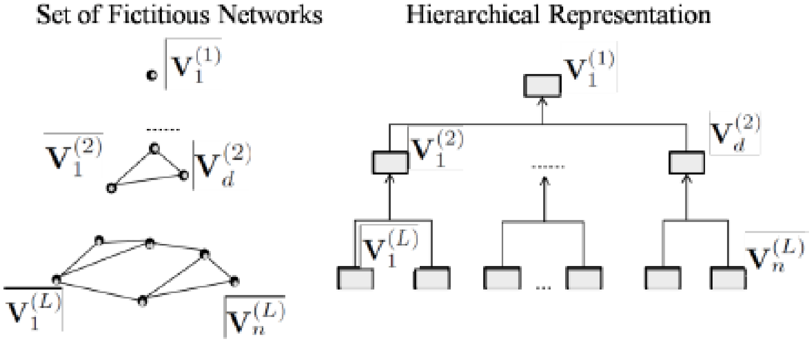


Figure 3.1: Hierarchical chart translated into individual fictitious networks.(from Buriticá et al 2011)

Due to vast amounts of information related to the system under analysis, "data analysis and pattern recognition techniques can be used advantageously" through means of modeling networks (Buriticá et al 2011). *Graph theory* is utilized in modeling networks, providing a graph consisting of nodes (vertices notated as *n*) and connecting edges (whose end-points are elements of the vertices). The vertices are connected using an *adjacency matrix* which defines the network structure. The network created defines the system as a whole, but is then subdivided into *communities*. From here, the *communities* of elements are grouped using patterns from the commonalities within the system, which is the basis of the clustering method. Subgroups (*k)* are formed, each containing a centroid representing the entire group. "Because a centroid is representative of elements within its cluster, it can be used as a complexity attenuator by considering only *k* centroids instead of *n* nodes; the number of clusters (and centroids) *k* at each level starts at 1 at the top and approaches *n* as moving down in the hierarchy" (Buriticá et al 2011). Graphical representation of the defined network displays the fictitious nodes and links at each subgroup level (as shown in figure 3.2 below).

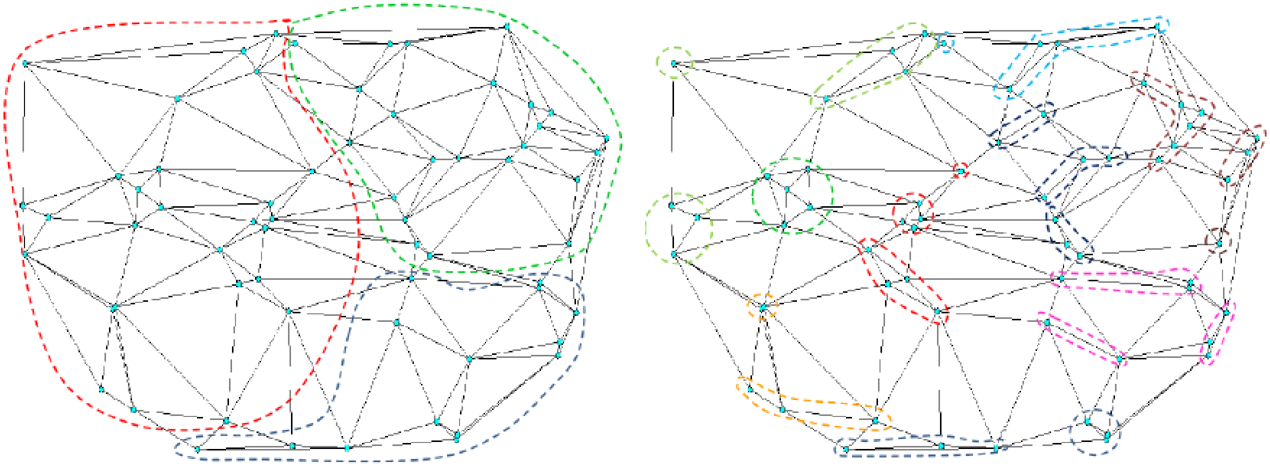


Figure 3.2: Network clustering at varying levels within the hierarchical representation (level two left, level four right) (from Buriticá et al 2011)

Using the graphical representation, optimization based decision making is conducted by finding optimizing variables in a multivariate objective function within a feasible region (region where the solution must reside) defined by constraints (e.g., distance, service availability). A *support network* is constructed containing individual *support centers* located solely at the centroids used to optimize the response to any disastrous event. For example, several solutions are considered for different approaches by changing the type and magnitude of various hazardous events. Figure 3.4 displays an example of an earthquake applied to the network, and the affected nodes and connecting edges. Observing how the different solutions perform based on the ability to provide assistance to affected locations, as well as cost (both contributing factors to vulnerability), the "best performance" is selected.

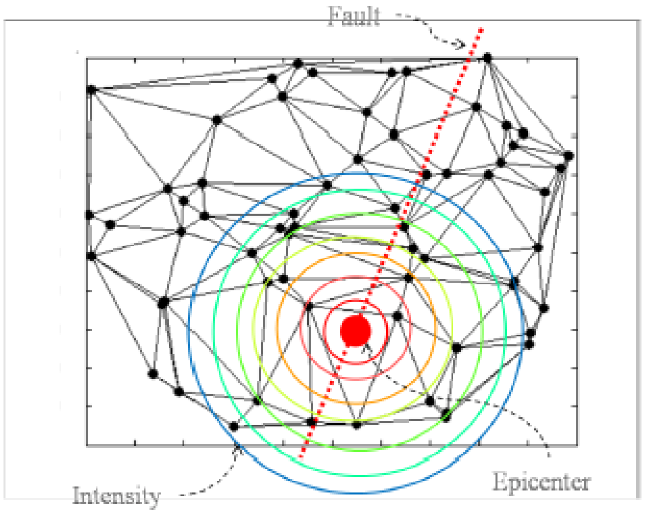


Figure 3.4: Affected area from simulated earthquake disaster

Overall, the “network hierarchical representation enhances the conceptual and computational efficiency of the optimum resource allocating problem (supply centers network) in case of a disastrous event. This strategy is defined so that the resource allocation problem suits the characteristics of linear programming, making the solution very efficient” (Buriticá et al 2011). Today’s increasing complexity of infrastructure systems in combination with population growth require simplified yet effective methods of analyzing risk to promote successful efforts to minimize this identified risk. This optimization based methodology using clustering algorithms meets these requirements, setting a framework for progressive infrastructure planning and resource allocation.

3.4 Inoperability Input-Output Model

Another method in assessing and managing risk is called the Inoperability Input-Output Model (IIM). This methodology is focused on the economic impact caused by or inflicted upon varying sectors (e.g., transportation). The IIM originated from Wassily Leontief, a Nobel Prize winner in economics, who developed an input-output model characterizing the interdependencies shown from the economic sectors of the economy (Haimes 2005). Assessment using the IIM is based on two factors: inoperability and economic loss. Inoperability defined as “the normalized production loss representing the ratio of unrealized production with respect to the "as-planned" production level", and economic loss as "the value of monetary loss associated with an inoperability value…[the] reduced demand for goods and services delivered by a perturbed sector…from either psychological factors or from the loss of production capabilities" (Haimes 2005).

The estimated dollar amount lost due to the 2003 Northeast American Blackout, previously discussed in the case studies, was calculated using IIM, demonstrating a post analysis application for this method. IIM only utilizes metrics associated with a monetary value, which is a limitation of this method unless intangibles such as injury and death are monetized. The IIM shall be used in conjunction with some other method of risk analysis to account for associated risks not defined by monetary value. Using multiple methods to determine the level of risk has the potential to provide a more accurate and detailed "big picture" understanding, resulting in more informative and cost economic decisions for resource allocation.

The monetary factors used to detect regional interdependencies are derived from the US Department of Commerce. The Regional I-O Multiplier System II (RIMS II), developed by the Bureau of Economic Analysis, releases regional multipliers from two primary data sources that reflect a specific location within the United States. These sources include: national input-output tables from the Bureau of Economic Analysis, representing 500 national-level industries, and "location quotients established from regional earnings and employment data" (Haimes 2005). Three of the RIMS II multipliers are as follows: 1) *outlier multiplier* showing the changes in a "sector's *production output* resulting from a $1 change in the demand for another sector's output, 2) *earnings multiplier* giving "the change in the *workforce earnings* of a sector resulting from a $1 change in the demand for another sector's output", and 3) *employment multiplier* providing "the change in the *number of workers* of a sector resulting from a $1-million dollar change in the demand for another sector's output" (Haimes 2005).

Transportation systems are straightforwardly applicable to input-output models. Industry sectors are directly affected by the transportation system, and reciprocally, effects from the industry sectors can alter the transportation system. From this relationship, the IIM follows the following form developed by Joost Santos and Yacov Haimes (Haimes 2005):

$$q = A^* q + c^*$$

Where,

$c^* =$ *a perturbation vector expressed in terms of normalized degraded final demand*
$A^* =$ *interdependency matrix indicating the degree of linkage of the industry sectors. Elements in a particular row can tell how much additional inoperability is contributed by a column industry to the row industry*
$q =$ *the inoperability vector expressed in terms of normalized economic loss*

Using the above equation as the basis of the IIM, individual infrastructure sectors causing the most economic impact can be depicted. Additionally, determining which sectors are most critical during the recovery phase is another feature of this method. Haimes, Santos and Williams (2005) performed an analysis to determine the sector inoperability and economic loss rankings due to a simultaneous 10% perturbation to the transportation system as well as a 10% perturbation to the utility sectors in the region. The losses determined are not directly caused by one source (or one sector), but instead “come from multiple sources and cascade through interdependencies to other sectors in the economy” (Haimes 2005). Table 3.2 below presents the top-10 most impacted sectors based on their inoperability metric and economic loss metric:

Table 3.2: Sector rankings based on inoperability and economic loss due to 10% perturbation to transportation and utility sectors statewide (from Haimes 2005)

Ranking:	**Based on inoperability:**	**Based on economic loss:**
1	Transportation	Transportation
2	Electric, gas, and sanitary service	Electric, gas, and sanitary services
3	Stone, clay and glass products	Miscellaneous services
4	Primary metal industries	Business services
5	Paper and allied products	Construction
6	Chemicals and allied products and petroleum and coal products	Retail trade
7	Metal mining and nonmetallic minerals, except fuels	Wholesale trade
8	Rubber and miscellaneous plastic products and leather and leather products	Health services
9	Coal mining	Depository and non-depository institutions and security and commodity brokers
10	Textile mill products	Food and kindred products and tobacco products

Observing which sectors are affected the most allows for optimized resource allocation and cost-benefit decisions. A few of the examples of potential solutions in minimizing the effect of a disruption to the transportation system include: providing specific routes mandatory for trucking, constructing redundant highways, requiring a staggered work schedule, promoting alternative methods of transportation, and increasing supplies at critical facilities (Haimes 2005).

The three risk-determining methodologies discussed in this section help policy makers, stakeholders, and emergency personnel understand where the interdependencies are located within a specific region. Each of the methods acts as a valuable tool in minimizing risk associated with interdependent infrastructure systems, but is incapable of analyzing all the risks within the study region. Due to the intricacy and nature of the infrastructure systems, along with the unknowns associated with hazards of all types, a full risk assessment is impossible. Limitations are present within each methodology; therefore by using more than one methodology some of these limitations potentially can be minimized. Continuous efforts to build upon these models will promote more accurate depictions of the behavior of infrastructure systems.

Another means of analyzing risk and identifying locations where vulnerability levels are high, is through the use of geographical information systems (GIS). GIS is a more visual approach which can be effective in showing the public current risk related issues. The following section discusses the implementation of this advanced tool.

Chapter 4

Geographical Information Systems as a Planning Tool

4.1 Using GIS

Using cartographic methods as a tool to analyze geographically dependent systems started in 1854, when John Snow pinpointed where the cholera outbreak in London initiated. He mapped where individual cases occurred to understand the distribution of the cholera outbreak. This visual method led to a contaminated water pump as the source of the outbreak (Brody 2000). The idea of gathering data and imposing specific data points on a map had been created. Then even one step further, maps were separated into individual layers, known as *photolithography*. Geographical information systems (GIS) are the definition of *photolithography* at its finest, thriving from the ability to seamlessly add numerous layers to depict an even greater picture than any single layer. GIS can be used for an infinite number of purposes, including acting as a defense tool. Today numerous aggressors are faced, including natural hazards, terrorist attacks, disease, and more. GIS allows planners and emergency personnel to access information more quickly allowing for more informed decisions on how to address these aggressors at the time of an incident as well as even during the planning stages.

The consequences of a natural, man-made or intentional attack can be mitigated through extensive planning. Planning lends to preparedness whether it be short-term or long-term. Short term preparedness refers to how individual emergency management teams, government officials, and other responding teams will react immediately after an incident has occurred. For instance, if the entire power system was shut down in the Denver Region, which locations are more important and would be addressed first in restoring their power supply. Long-term preparedness refers to proper planning of the infrastructure system, such as developing alternative power supply sources so if the main system shut down, there would be a backup source to allow for essential functions to continue operating.

GIS has a community aspect allowing multiple organizations and individuals to come together to create a unified vision. Hazard planning requires extensive cooperation amongst several groups from government departments to the utility companies to the fire chiefs. Each group has an individual function, but all together the same goal; to protect the people and the community's assets. This community of planners comprises a system of data gathering. Sharing data and helping each group understand which data are vital in taking the next steps of developing specific plans. For instance, a map of the location of a particular earthquake fault line does not help planners unless they know where this fault line is located in relation to the population, the infrastructure systems, and other critical assets, as well as where it can have the most economic effect if an incident were to occur. However, this detailed information comes from various organizations and agencies, including those shown in figure4.1. GIS provides the backbone for creating these maps that tell a story, laying out the potential scenarios and possible consequences from the occurrence of a potential hazard.

Figure 4.1: Data sharing in the GIS community

Different organizations sharing their data together not only brings together a more detailed and accurate model, but also helps develop relationships amongst these groups. A critical part of emergency management and mitigation is communication, elevated by these relationships. Data sharing opens up lines of communication, ultimately creating a network of resources. A single terrorist attack or violent act of nature, such as an earthquake, can catch any of those groups off-guard if they do not have the support from the other organizations. Humans react instinctively when prompted by a crisis, and if relationships are developed prior, our natural instinct will be directed to a network of trust.

By modeling potential scenarios through GIS, different groups can determine at that time what other resources they need that can only be obtained through another organization. This eliminates unnecessary chaos in the time of an actual event. Combining resources will help protect critical assets and save valuable time that can be allocated to other areas.

"In this new post-9-11 era, a new philosophy is required – a philosophy of shared responsibility, shared leadership and shared accountability. The federal government cannot micromanage the protection of America," Ridge, Homeland Security Secretary, said in 2004 when he announced the creation of a national intelligence network (Kataoka 2007).

GIS helps planners, emergency management teams, as well as the stakeholders, gain a grasp of the level of risk leading to vulnerability exposure. GIS assesses time-and-space relationships, recognizes patterns, and correlates seemingly disconnected events to allow for decision makers to take action (Kataoka 2007).

For the purpose of this research, GIS is used as a tool to analyze spatial areas where vulnerability resides. The program, ArcGIS, developed by the Environmental Systems Research Institute was used to overlay maps for this research (ESRI 2011). Using ArcGIS, critical areas can be determined and observed, showing their effects on surrounding areas if a particular stressor were applied. Critical areas include areas with social vulnerability, and where infrastructure assets and key facilities are located.

For data used in ArcGIS regarding the effect of a natural stressor within a defined area, the program HAZUS-MH may be used in conjunction by simulating various scenarios emulating a natural disaster and creating output to be used specifically in ArcGIS. The next section discusses the methodology and capabilities of HAZUS-MH.

Chapter 5

HAZUS Loss Estimation Program

5.1 Using HAZUS-MH

HAZUS-MH (current version: MR4) is a program developed by the Department of Homeland Security Emergency Preparedness and Response Directorate, Federal Emergency Management Agency Mitigation Division in Washington, D.C. It is used to estimate direct and indirect losses due to multiple hazards. Loss estimates allow governments at all levels (federal, state and local) to develop mitigation plans, and promote emergency response preparedness. These loss estimates are determined by using an inventory of infrastructure elements and specific population characteristics for a specific study region. National databases supplement HAZUS-MH with important information including: demographics, building occupancies and square footage, location of critical structures (e.g., bridges, hospitals and fuel refineries), economic parameters, as well as other pertinent data. The program has been designed to allow users to add to the built-in database for more detailed analysis. More specific, updated, and precise data naturally lend to more accurate results (FEMA 2010). HAZUS-MH is the multi-hazard version of the original version developed for earthquakes. The vision statement for the original version provided by FEMA is:

> *The earthquake loss estimation methodology will provide local, state and regional officials with the tools necessary to plan and stimulate efforts to reduce risk from earthquakes and to prepare for emergency response and recovery from an earthquake. The methodology will also provide the basis for assessment of nationwide risks of earthquake loss…* (FEMA 2010).

In the scope of this thesis, HAZUS-MH is used for simulating an earthquake scenario. The following discusses the specific application of using HAZUS-MH for loss estimations due to an earthquake. HAZUS-MH has developed a framework methodology constructed by six components: Potential Earth Science Hazard, Inventory, Physical Damage, Induced Physical Damage, Direct

Economic/Social Loss and Indirect Economic Loss. These components are interdependent upon one another, with some of the outputs acting as inputs to other components, identified as "modules" in Figure 5.1. Each of these modules contributes to the total loss estimate. The framework of HAZUS-MH allows users to input additional modules applicable to their needs.

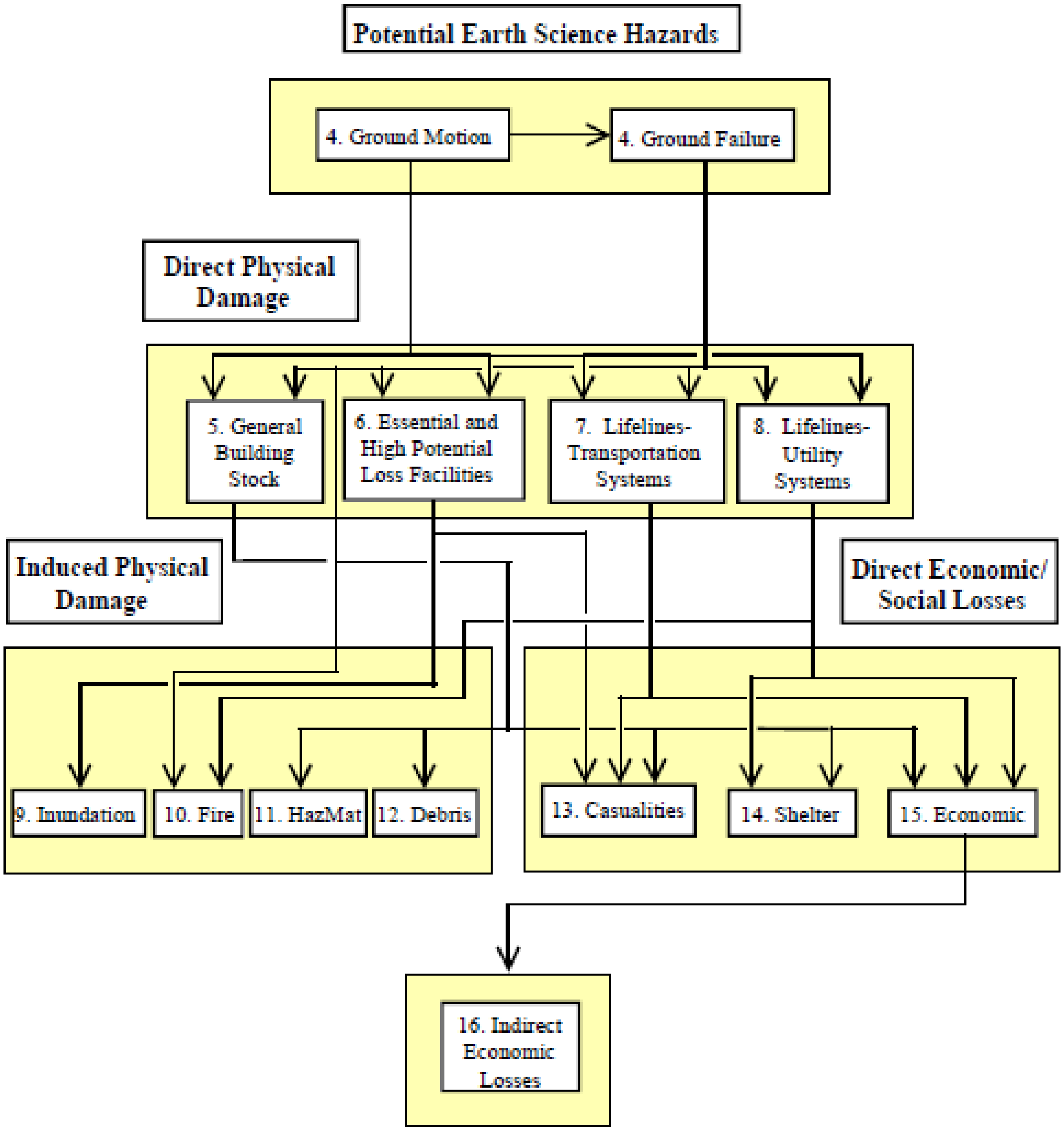


Figure 5.1: HAZUS-MH MR4 Earthquake Loss Estimation Methodology Framework Flowchart (provided by FEMA (2005))

The methodology of HAZUS-MH has been tested by judgment of experts, and against records from historical earthquakes supporting the validity of the loss estimates. "HAZUS-MH Earthquake

Model has provided a credible estimate of such aggregate losses as the total cost of damage and numbers of casualties" (FEMA 2010). Even though this program provides a good basis of an estimate, there are a few limitations indicated in the HAZUS-MH MR4 Technical Manual as follows:

- Individual losses for specific structures are not determined, instead the results are averaged for a group of similar structures
- Losses in an extensive urban region from earthquakes with a magnitude less than M6.0 tend to be overestimates
- The embedded attenuation functions in the Earthquake Model corresponding to the Eastern U.S. are more conservative due to the uncertainty of the ground motion.
- The model assumes the same Site Class soil type for all sites within the study region unless the user supplies a detailed soil map digitally formatted with the same site class definitions of the 1997 *NEHRP Provisions*

Implied amongst the limitations listed above is the embedded inventory of data. HAZUS-MH MR4 provides generalized data, which allows its utilization by those who do not have access to detailed local data. For more specific applications, however, additional data provided by local affiliations are required. In the scope of this research for providing a regional vulnerability assessment, the default data inventory is used, including building replacement costs primarily derived from 2002 R.S. Means industry-based cost estimates. The types of data collected for this inventory are shown in Table 5.1.

Table 5.1: Generalized inventory data in HAZUS-MH MR4

Classification	Type of Data	Detail of Data
direct damage data - buildings and facilities	residential	basic structural system, building height, seismic design criteria, nonstructural elements, occupancy, regional building practices, variability of building characteristics within the classification
	commercial	
	industrial	
	agricultural	
	religious	
	government	
	educational	
essential facilities	hospitals	ground motion parameters are determined at the individual facilities location, expected loss of functionality for each of these facilities is recognized
	police stations	
	fire stations	
	schools	
high potential loss facilities	nuclear power plants	loss of these facilities would cause extensive damage
	dams	
	military installations	
direct damage data - transportation systems	highways	category includes bridges, roadways, and tunnels, also fuel, dispatch and maintenance facilities associated with the operation of these systems
	railways	
	light rail	
	bus	
	ports	
	ferries	
	airports	
direct damage data - lifeline utility systems	potable water	includes the systems and their components
	waste water	
	oil	
	natural gas	
	electric power	
	communication systems	
hazardous materials facilities	facilities handling or storing hazardous materials	these facilities present hazards because of their toxicity, radioactivity, flammability, explosiveness, or reactivity; data includes facility location, and type and amount of hazardous material
direct economic and social loss	demographics	from Census

indirect economic data	demographics	from Census & Dun and Bradstreet Company, data includes change in employment, change in tax revenue, increase in imports and exports, supply and product inventories and unemployment rates

In this thesis, HAZUS-MH MR4 is not used to perform a detailed analysis to identify specific buildings and facilities, but instead used to identify and isolate areas within the Denver Region where higher levels of vulnerability exist and need to be addressed. Therefore, the data described above are considered sufficient for this objective. Local governments should, however, take advantage of the capability of adding to or altering the data in the program's inventory. For example, HAZUS-MH MR4 approximates the dollar value for each of the fuel refineries in the region. Actual monetary values could be collected for each refinery in the study region, and adjusted in the data inventory to provide a more accurate cost estimate. Analysis in one study region can be significantly different from analysis in another region, due to the extensive number of variables that impact the outcome. This program was developed with the intention of maintaining flexibility to aid users in accounting for these variables.

The advantage of flexibility for inputting data is also available for analyzing hazard scenarios. HAZUS-MH can be used to model earthquakes, wind and floods, each with user selections for various hazard parameters. This program cannot be used to approximate the damage due to specific technical disasters such as a freight rail accident or other man-made disasters. However, the inventories provided in HAZUS can be extracted for use in ArcGIS to allow for analysis using a technique of overlaying individual layers and observing the physical and geographical interdependencies. In this thesis, HAZUS-MH MR4 was used as a tool for simulating potential earthquake movement that would affect the Denver Region. Flooding analysis was performed separately using FEMA flood zoning maps instead of HAZUS-MH due to the complexity and level of detailed information that would need to be gathered to appropriately use the program's capabilities. In the Earthquake Model, users can specify the appropriate attenuation function to represent the ground shaking behavior within their study region. Detailed soil maps can be imported, or the site class soil type for the entire study region can be defined. Other user defined parameters include: magnitude, fault type (e.g., strike-slip, reverse), depth, and length of fault line.

Earthquake scenarios which HAZUS-MH can simulate are historical earthquakes or generated events. The program contains over 8,000 historical earthquake records, consisting only of earthquakes with magnitudes greater than 5.0. The historical earthquakes are defined by their epicenter location, depth and magnitude. For attenuation relationships identified with the Western United States, the user also specifies the fault type, dip angle and orientation of the fault. For those identified with the Central Eastern United States, the epicenter location and depths are integrated within the attenuation relationship. The probabilistic seismic hazard contour maps can also be defined by the user, while the default maps used in the program are from the updated National Seismic Hazard Maps (2002) developed by USGS. These maps provide the estimates of the Peak Ground Acceleration and spectral acceleration at periods of 0.3 and 1.0 seconds. Probabilities for the ground shaking estimates are taken from eight defined hazard levels specified in the Technical Manual (FEMA 2010). These hazard levels range from the ground shaking with a 39% probability of being exceeded in 50 years to a ground shaking with a 2% probability of being exceeded in 50 years. User defined maps are preferable in place of the National Seismic Hazard Maps when the proper attenuation relationships are not available for a specific scenario event. The scenarios run for this research do not include a probabilistic assessment with USGS National Seismic Hazard Maps because Colorado seismic behavior has not been explored enough to provide these hazard maps with accurate data. The maps underestimate Colorado’s earthquake hazard, resulting in lower loss estimates determined by HAZUS (DOLA 2007). Instead, a deterministic analysis was used for examining the consequences related to an earthquake in the Denver Region. A deterministic analysis allows the user to input a specific scenario, such as simulating an earthquake with the same epicenter and hypocenter as an historical earthquake occurrence for a specific magnitude. Specific input parameters used in the deterministic scenarios performed will be discussed in later sections. The following section discusses the various stressors applicable to the Denver Region including the earthquakes used in the HAZUS-MH simulation as well as the risk associated with the transportation of hazardous materials.

Chapter 6

Stressors in the Denver Region

6.1 Defining Stressors

Infrastructure interdependencies are exposed when stressors impose on a system. These stressors are placed in three categories: natural, man-made, and intentional; each potentially capable of producing a high degree of severity onto one or more of the infrastructure systems. The hazard level associated with each potential type of threat is dependent on the location to which an event occurs. Locations vary tremendously from a large city to a small town; every individual region maintains a unique set of characteristics such as types and magnitude of natural disasters likely to occur, population densities, building types, important structures, building codes used, activity level, etc. These characteristics compose a region's "profile", and are important to identify, allowing for proper development and mitigation planning addressing the location of interest. The following describes potential stressors associated with the Denver Region

6.2 Natural Disasters

Dennis Mileti, Professor Emeritus at the University of Colorado at Boulder, discusses in his book, *Disasters by Design* (1999), how disaster losses are "the result of interaction among three systems and their many subsystems". The three systems are broken down as follows: the earth's physical system, the human systems, and the constructed system, each forming a piece of the puzzle (Mileti 1999). Within the earth's physical system category are natural disasters. The topic of natural disasters typically brings to mind major events such as the earthquake in Haiti in 2009 or the recent tsunami in Japan 2011. Therefore, many residents in the Denver Region typically do not associate major natural disasters with the area since it has never experienced a natural disaster at the magnitude of such events. However, it is only a matter of time until some disaster will occur, leaving the Denver Region crippled if careful planning is neglected. Figure 6.1 below provides the property damage associated with the six hazard categories defined and quantified by SHELDUS, a county-level hazard data set for the U.S. The monetary value associated with each of the hazards from the database does not accurately display the potential of a serious hazard to the stakeholders. Solely basing decisions on figures similar to figure 6.1 shown below, neglects the likelihood of an earthquake causing damage for example, or flooding significantly destroying property. Although such an event has not occurred in the past forty years, the possibility remains, and the resulting damage will be magnified with the continuous increase in urban development. Figure 6.1 shows that severe storms have caused the most property damage in the Denver County, making this stressor important to recognize. Severe storms/thunderstorms are not examined later in this thesis since there are several possible scenarios and many unknowns it would be difficult to examine specifically, but they should not be ignored in infrastructure planning and hazard mitigation efforts.

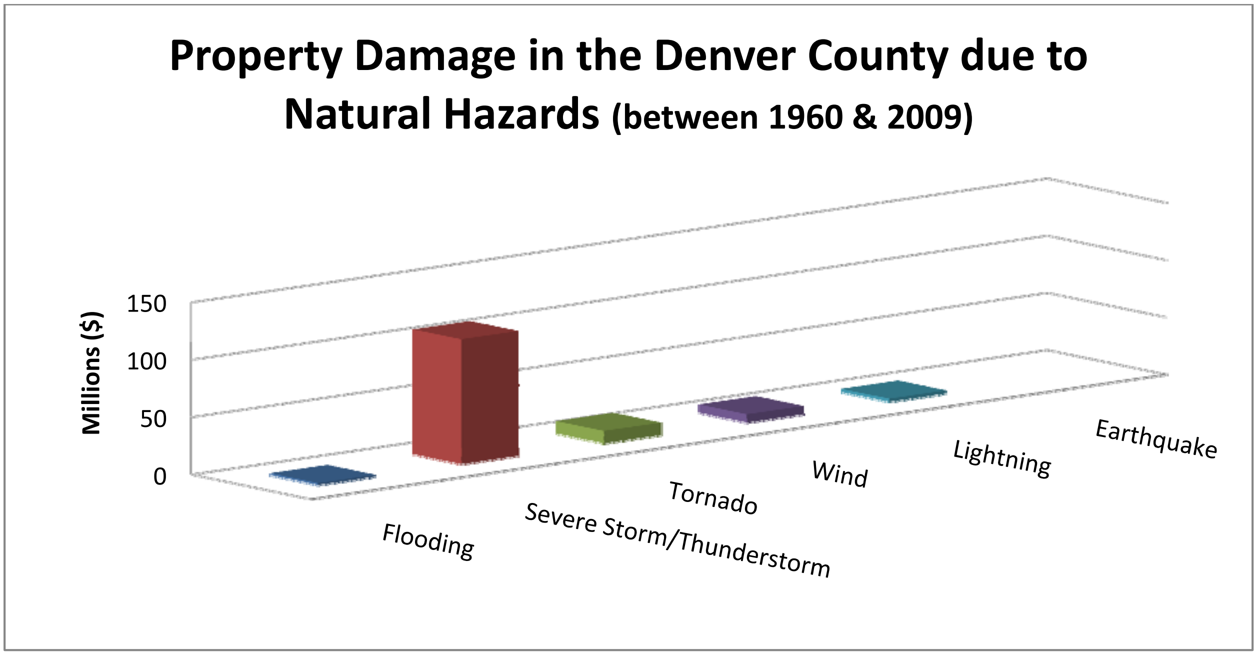


Figure 6.1: Property damage in the Denver County (data from SHELDUS)

Preparing for a natural disaster requires knowledge of the possibility and magnitude of the event, as well as knowledge of the area over which the event could occur. The natural hazards the Denver Region are susceptible to include flooding, earthquakes and severe storms (thunderstorms, winter storms, and tornadoes). Each of these hazards and how they are associated with the Denver Region is further discussed in this section.

Flooding:

Flooding has always been highlighted on the list of natural disasters for the Denver Region. Frightening statistics provided by the 2001 Colorado Water Conservation board show that more than 250,000 Coloradans reside in flood plains, 2,000 of these in Denver. A total of 65,000 homes and 15,000 businesses are included in these flood plain areas. The value of these homes and buildings, in addition to the land value, in the identified flood plain regions totals $16 billion. However, it is interesting that at this time, there were only 14,000 flood insurance policies filed in Colorado (Johansen & Proctor 2005). This shows that even though the risk lies in living in flood plain areas, people tend to disregard flooding as a major threat. One of the main issues in sustainable development stems from this continuous development in these flood prone areas.

Past flooding events affecting the Denver Region have not been forgotten by the City and County of Denver. One event that shook Denver occurred in 1965 when a storm hit Douglas County, producing fourteen inches of rain in a three hour time frame. The high volume of water developed into a twenty foot wall of water moving down the South Platte River directly into downtown Denver. Sixteen bridges were destroyed along the Platte and sixty-two businesses. In fact, 33 communities in Colorado were declared as federal disaster areas. The damage resulted in $540 million in losses and 21 fatalities (Johansen & Proctor 2005). Following this event, the Urban Drainage and Flood Control District have developed the Flood Control Master Plan, which has minimized the potential risk greatly (OEM 2010).

Global climate change is expected to lead to an effect on the frequency and magnitude of natural hazards. For instance, the climate change has lead to an increase in hurricane activity, resulting in more intense events (USGCRS 2009). Hurricane storms from the Gulf of Mexico and the Pacific Coast have an effect on Colorado. The effects from pacific storms include significant rain experienced along the

Front Range, resulting in floods. In August 1938, a Texas hurricane left its footprint in Colorado five days later with significant rainfall. The flood resulting from this downpour destroyed entirely the Town of Morrison (located west of C-470 along Colorado Route 8), killing six people (Johansen & Proctor 2005). This event is interesting because currently the area is completely redeveloped. The people who reside there are not aware of this past event that could potentially reoccur. A major issue remains in the current development occurring in Colorado, including the development in the Denver Region. Simply stated, development in or near a floodplain region increases flooding risks. Additionally, "the built-up environment creates localized flooding problems outside natural floodplains by altering or confining drainage channels...it reduces the stream's capacity to contain flows and increases flow rates downstream" (DRCOG 2009). The human desire to expand and further develop has in turn commenced a problem saturated with risk. This risk associated with flooding is further discussed in chapter7.

According to the 2009 Denver Regional Natural Hazard Mitigation Plan prepared by the Denver Regional Council of Governments, urbanization is the cause of increasing the losses due to a flood event (DRCOG 2009). In less than a decade, between 1990 and 2000, fifty square miles of land was urbanized in the Denver Region. This urbanization has turned once natural land into developed land that does not absorb rainfall as easily or at all (e.g., roads). "Urbanization increases runoff two to six times over what would occur on natural terrain" (DRCOG 2009). Again, this demonstrates why urban locations have increased vulnerability. Less drainage, more vertical growth in building structures and an increase in population act as a recipe awaiting large consequences. The likelihood of another major flooding event to occur in the future in the Denver Region should not be underestimated. Another natural hazard that is not possible to occur in the mind of many in the Denver population is an earthquake; unfortunately this is not true, as expressed in the following section.

Earthquakes:

Colorado has not been known for catastrophic earthquakes, making it easy to ignore the potential damages one could cause. In fact, the program SHELDUS created by the University of South Carolina (a spatial hazard events and losses database for the United States), shows the Denver region specifically having no property damage loss due to an earthquake as of 2009 (SHELDUS 2009). The current economic loss figures (or lack thereof) due to an earthquake in the Denver Region result in a low level of concern in planning for a potential earthquake incident. However, the issue remains a concern because the fault lines in Colorado have not been greatly explored, primarily due to lack of funding. In 1970 eight faults were reported in Colorado, and by 1998 more than 90 were declared, showing the number of unknown faults is greatly unknown. Several scientists in the state argue that the risk associated with an earthquake hazard is “lower than justified” (DOLA 2007).

A handful of faults have been studied in considerable detail due to investigations that were conducted by the Bureau of Reclamation for their dam safety program. Apart from these studies along with the studies done by USGS of the Cheraw and south Sangre de Cristo faults, few earthquake hazard studies have been performed (DOLA 2007). Due to the lack of historical data and the knowledge that earthquakes occur infrequently in Colorado, the ability to estimate the future location and timing of an earthquake is difficult. Seismologists can only predict that an earthquake at a magnitude of 6.5 will occur sometime in the future. An earthquake of this magnitude can result in extensive damage. The last earthquake that occurred in Colorado of this magnitude was on November 7, 1882 located in the northern Front Range west of Fort Collins (DOLA 2010). The following table 6.1 shows the 1882 earthquake along with three of the largest historical earthquakes near the Denver Region since 1867. The information was prepared by the Earthquake Subcommittee, Colorado Natural Hazards Mitigation Council (DOLA 2010). The intensity levels are based on the Modified Mercalli Intensity VI-XII.

Table 6.1: Largest historic earthquakes near the Denver Region

Date:	Location:	Magnitude:	Intensity:
November 7, 1882	North-Central CO	6.5*	VII
January 4, 1966	N.E. of Denver	5.0	V
August 9, 1967	N.E. of Denver	5.3	VII
November 27, 1967	N.E. of Denver	5.2	VI

*magnitude for this earthquake was based on historical qualitative reports

The previously mentioned earthquake that occurred on November 7, 1882, was the largest earthquake in Colorado. The effects were seen from Denver all the way to Laramie, Wyoming. Residents in Utah and Kansas also slightly felt the disruption. This earthquake resulted in the electricity being cut off in Denver "after an iron bolt that connected an engine-driving pulley was broken in two at the electric power building" (USGS 2009). Denver was the location of the first electric generating station built west of the Mississipi River in 1881(Colorado.gov 2009). Another of the earthquakes shown in the table 6.1 above, occurring in northeast Denver on August 9th, 1967 reached a magnitude of 5.3. Resulting damage from this earthquake mainly took place in Northglenn just north of Denver. Damage included failure of concrete pillars at a church, and cracked concrete floors and walls at a school (USGS 2009). The cause of this earthquake was initially linked by geologist David M. Evans in 1962 (Monroe & Wicander 2009) to be a direct result of human tampering at the Rocky Mountain Arsenal. Contaminated wastewater was injected into a disposal well 12,054 feet (3674 meters) below the surface (Monroe & Wicander 2009). Evans' theory was later proven true through studies, including a study performed by USGS showing that the "pumping of waste fluids into fractured rocks beneath the disposal well decreased the friction on opposite sides of fractures and, in effect, lubricated them so that movement occurred, causing the earthquakes that Denver experienced" (Monroe & Wicander 2009).

In fact, due to the injections at the Rocky Mountain Arsenal, 1,300 recorded earthquakes occurred between January 1963 and August 1967. A similar reaction of ground movement occurred at Rangley

Field in northwest Colorado back in 1970, attributed to water flooding the field. From the seismic causations seen at these two sites, USGS pursued a study using abandoned wells to see if injecting water into the earth directly caused these tremors. Initially fifty recordings of activity occurred each day when the injections were ongoing. Once the injections were ceased, the activity drastically reduced to only one to two per day. For another check, USGS again started to inject fluid to see if the pressure build up would again increase the number of episodes per day. As expected, the activity increased again to fifty recordings per day (Shirley 2001). The direct correlation between human interjection and the amount of seismic activity occurring below Colorado's surface must be addressed to understand seismic activity that can be preventable.

Currently there are approximately one-hundred active faults running through the state, and these are only the known faults. Three of these fault lines in the state have been identified as faults capable of producing an earthquake of a magnitude of 7.0 or greater. These faults include: Cheraw fault, Northern Sangre de Christo Fault, and the Southern Sawatch Fault (Hake 2009).

The Cheraw fault potentially could be a major threat to the Denver Region. The Director of the Colorado Geological Survey, Vince Matthews, described that due to recent earthquakes in Colorado in 2009 (a 3.9 magnitude earthquake east of Eads in Kiowa County on August 16th, and a 3.7 magnitude earthquake north of Craig on August 17th), geologists have discovered that the Cheraw fault may actually run further east than previously identified, and potentially more powerful than currently predicted (Christiansen 2009). Matthews stated that, "if the fault does indeed extend out there, then it's possible that it could have a larger earthquake than what is thought now", even reaching a magnitude 8.0 earthquake (Christiansen 2009). The possible damage resulting from a nearby 8.0 magnitude earthquake could be detrimental since the Denver Region was not designed to resist an earthquake of this magnitude. One particular concern is the number of masonry structures in the Denver Region. Several residencies and commercial buildings were built using unreinforced masonry bricks, which are highly "susceptible to earthquake damage" (OEM 2011). The Colorado Geological Survey (CGS) performed an analysis (published in 2007 DOLA Earthquake Evaluation Report) to estimate the economic loss resulting from a magnitude 6.5 earthquake along the Rocky Mountain Arsenal Fault, within 500,000 feet (approximately 150km). Using the program HAZUS to run the analysis, CGS determined the total direct economic loss in Colorado would be $24.83 billion, making it the most damaging fault in Colorado. Following the Rocky Mountain Arsenal Fault on the list of the top five most damaging faults, in order, are: Golden ($22.08 billion), Rampart Range ($18.26 billion), Walnut Creek ($13.25 billion), and Ute Pass ($12.88 billion). The Denver County ranks third in the counties at greatest risk (based on monetary loss, number of fatalities, and loss ratios), behind El Paso County and Jefferson County (DOLA 2007). In chapter 7, two earthquakes were simulated to observe the physical and economic damage resulting in the Denver Region. Both earthquakes simulated had a Maximum Considered Earthquake of moment magnitude 6.5, one located at the Rocky Mountain Arsenal Fault and the other along the Golden Fault.

Winter storms:

Winter storms in the Denver Region typically translate into traffic delays (especially due to traffic accidents), and damage to essential utilities (e.g., water pipes, power lines). These winter storms have in the past put the Denver Region into a state of paralysis. Table 6.2 below identifies major winter storm events in the Denver Region, and provides a brief description about the event itself and the resulting effects:

Table 6.2: Winter Storms Affecting the Denver Region

Type of Storm:	**Date:**	**Description:**
Blizzard	December 2006	-snow reached three feet deep in some areas -travel affected for days -a presidential emergency declaration set to assist communities after the event
Blizzard	March 2003	-several highways closed in Colorado -reduced visibility in Denver (including the boulevard to Denver International Airport -presidential emergency declaration was issued
Windstorm	February 1999	-a Chinook windstorm with 120 mph and greater winds (resulted in $3 million worth in damage in Denver)

		-thirty 70-ft high power poles were damaged (some supporting high voltage power lines directly from power plants) -10,000 residents experienced power outages
Blizzard	October 1997	-14-31 inches of snow in metro Denver -no visibility in some areas -major highways and roads were closed -Denver International Airport was shut down (4,000 people stranded at DIA)
Hail Storm	October 1994	-northwest Denver experienced ¾ to 1/12 inch diameter hail -aircraft was damaged and pilots injured at Stapleton International Airport
Blizard	March 1992	-Denver received up a foot and a half of snowfall with winds gusts up to 52mph -I-70 east and I-25 north and south were closed -power outages affected several homes and stores
Blizzard	March 1990	-streets, highways, schools and businesses were all closed -stranded motorists were rescued by the police and National Guard on the Denver-Boulder Turnpike -airliner slid off the runway at Stapleton International Airport

*Winter storm information provided by DOLA Division of Emergency Management (2011)

In Colorado winter snowstorms have been known to occur from early September to late May. Record damage figures from past winter storm events in Denver show that these storms cannot be taken lightly. For example, the blizzard of March 2003 shown in table 6.2 above , resulted in insurance claims over $33 million The eighteen major severe storm events in the Denver Region between 1960 and 2007, incurred a total of $2,637,024 worth in property damage (DRCOG 2009).

As one can infer from Table 6.2 above, the main issues directly correlated between winter storms and vulnerability in the Denver Region include: minimizing or even halting the use of the roadway system (from highways and major roads, to side streets), shutting down the Denver International Airport, power outages, and using a majority of emergency personnel available to address stranded people. Winter storms prevent typical daily operations from occurring. Characteristically people are forced to stay at home, shipments cannot come in or go out of the city, many people are without heat, etc. Observing the severity of these historical winter storms in the Denver Region shows the need for infrastructure planning to not ignore the vulnerability each of the storms brings to the area.

Severe Storms:

In the Denver Region, severe storms include thunderstorms, winter storms, and tornadoes. Many of the seventy thunderstorms that occur each year in Colorado are accompanied by hail or lightning (OEM 2011). While hail and lightning are not typically hazards that are examined in infrastructure planning, each remains as a substantial threat. Hail storms result in physical damage, particularly involving vehicle and roofing damage, leaving a major economic dent. For instance, the hail storm in July of 1990 resulted in $625 million worth in damages. Between 1995 and 2007, Denver experienced 153 individual hail storm events (DRCOG 2009). Ways to minimize the damage caused by hail storms are focused on new materials and specific construction methods, versus overall infrastructure planning.

Lightning attacks are another product of thunderstorms, “killing more people each year in Colorado than in any other weather related phenomena” (OEM 2011). Since 1980, 88 people have been killed and 400 injured due to lightning strikes in the state of Colorado, three of these fatalities and twelve of the injuries occurred in the Denver Region (NWS 2010). Lightning strikes are highly unpredictable, and the resulting damage isolated, making it uneconomical to spend money on researching ways to transform the existing infrastructure system to resist this potential damage.

6.3 Man-Made Hazards

This paper examines man-made hazards and intentional attacks separately. Man-made hazards are created because mankind has developed systems, with the potential to result in a disaster. These systems pose a threat on society by containing human fallibility, whether the resultant error is in the system itself or the location of the system. For instance, an isolated system may not pose a physical threat unless the environment where the system resides generates vulnerability, such as where a natural disaster could occur or where humans interact nearby, introducing new vulnerabilities.

Hazards caused by man include, but are not limited to: fire ignition, hazardous materials, transportation vehicles (cars, airplanes, trains, etc.), structure failures, pipeline breaks, technology, water security and electrical outage. Societal development includes more opportunities for human error, contributing to the potential hazards previously listed. For instance, a single electrical outage can escalate into a more severe situation, including a shortage in drinking water. Water systems have been designed with a dependency on electricity to operate pumps to provide potable water. When drinking water is not available, people resort to drinking contaminated water, which can result in illness. The city of Milwaukee experienced a similar situation in 1993, leaving 400,000 people ill and killing 104 individuals from drinking water contaminated by the deadly parasite called cryptosporidium (911Water 2011). Only 2.5 percent of the water on earth is fresh water, making the protection of water supplies even more critical. “Generally, areas of high-density populations stress water resources. Adding to this problem, population is increasing in areas where natural hazards – earthquakes, hurricanes, floods, and droughts – are most severe. Such natural hazards can disrupt potable water distribution and destabilize population centers” (Tindall & Campbell 2010). Denver falls into the category of populated areas where potable water is distribution critical, creating a potential man-made hazard.

A recent, and devastating example of a man-made hazard, resulted from the tsunami in Japan on March 11, 2011. The tsunami caused by an off-coast earthquake outside of Japan reached the Fukushima Daiichi Nuclear Power Station, causing “explosions and leaks of radioactive gas” (NYT 2011). A natural disaster resulted in a domino effect, triggering a man-made hazard: a nuclear reactor failure. The first design weakness was the inability to provide power to the cooling systems in the nuclear reactor to prevent the fuel rods inside from overheating. Second, the physical design of the vessel encapsulating the nuclear reactor was not robust enough to seal the system in case of a radiation leakage. The containment vessel is a Mark 1 reactor designed by General Electric from the 1960s. This model was appealing at the time for its low cost and constructability, however, weaknesses were later identified (Zeller 2011). A system housing hazardous materials (such as in the Fukushima nuclear plant) that is not robust enough to withstand a natural disaster or an electrical outage must have a backup design. Infrastructure designs are becoming more complex and sophisticated, requiring more attention to their design safety.

All developed areas, including the Denver Region, have acquired potential man-made hazards. Developing in the floodplains is a notable hazard which several communities have brought upon themselves. Flood zones clearly identify areas that represent a risk for development; however, Denver has rapidly grown into a "hotspot" for many businesses and residences, enticing further growth. In order to protect the Denver Region from floods, three dams were built: Cherry Creek Dam, Chatfield Dam, and Bear Creek Dam (built in this order) (USACE 2011). Dams act as a wall protecting citizens from the effects of flooding; however it can be argued that the dams present a false sense of security to habitants in the floodplain zones. This apparent security "encourages human occupation of the floodplain, thus introducing the elements of future disaster that may be more serious than if nothing had been done; such a disaster can cause severe and unnecessary losses of resources; it discourages the economic use of land; and it is not cost-effective" (Arnold 1975).

Transporting hazardous materials through heavily populated areas raises concern of human safety. Two of Denver's main transportation arteries (I-70 and I-25 highway corridors) serve as main routes for transporting hazardous materials. Both highways pass through highly populated areas within the city (OEM 2011). The threat level from these hazardous materials is high, enough so to designate detours around Denver during the 2008 Democratic National Convention. Temporary routes were designated guiding shipments to exterior routes (Truckinginfo 2008).

Even prior to the Democratic National Convention, concerns related to the transportation of hazardous materials through the city of Denver were well known, leading to the Denver Fire Department installing a hazmat team in 1985. The Denver hazmat team has continuously been ranked in the Firehouse Magazines annual National Run Survey as one of the teams with the most incidents per year. One of Denver's hazmat units, HAMER 1, was designated for having "the most hazmat responses in the country in 2005, with 1,637, and was second in 2006 with 1,704" (Burke 2007). Hazardous materials have played a key role in Denver's vulnerability, along with many other man-made hazards with the potential to contribute to a major disaster.

6.4 Intentional Attacks

Individuals behind intentional attacks typically utilize man-made hazards as mechanisms to inflict damage to the masses. For instance, if the Hoover Dam were attacked, this "could affect water and power availability in the Western United States", which "denotes why the U.S. Intelligence Community is concerned about these types of possibilities" (Tindall & Campbell 2010). The key to terrorists is to find a node linking interdependencies, creating a cascading effect to an entire city or region. Although the Denver Region has not experienced any major terrorist attacks, the possibility cannot be eliminated. In 2010, Denver was identified as "a frontline in the fight against homegrown terrorism…one of the places to watch on the homegrown terrorism radar" (Obert & Brady 2010). Even one of Denver's previous airport shuttle drivers, Najibullah Zazi, was "accused of having ties to Al-Qaeda" (Obert & Brady 2010).

Intentional attacks are presented in several forms, including: biological, chemical, explosions, nuclear threat, and radiation threat, all man-made agents (READYColorado 2011). Accounting for each of the threats mentioned is virtually impossible, therefore mitigation is oriented toward minimizing the existing interdependencies within the infrastructure system and making each system more robust. Additionally, critical structures must be identified and protected as much as possible.

Denver needs to be prepared for an intentional attack within the regional boundaries, as well as also be prepared for the indirect effects of a distant attack. In 2006, the effects of an alleged terrorist plot that occurred in Britain reached the Denver International Airport (DIA), causing significant flight delays (TheDenverChannel.com 2006). Raising the security alert level can typically cause congestion and/or instill a sense of uneasiness. Furthermore, if an intentional attack were to occur in Denver at the same time as delays at DIA, forcing an evacuation, would Denver be prepared? All situations need to be examined in the case of an emergency, including the implementation of redundant systems.

Weaknesses intertwined in any system often are not known until a stressor is applied, unveiling perilous system ties. To add to the complexity, the time when the stressor will be applied is also unknown. Future climate changes are “unlikely to be experienced in such a smooth manner because human-induced changes will be amplified in some years by naturally fluctuating conditions reflected in potentially sudden and dramatic changes at the regional or local level, where transportation infrastructure is located” (NRC 2008). The time and location of a man-made hazard or an intentional attack is also unknown due to an unlimited number of independent variables. The uncertainty must be counteracted with proactive measures taken toward decreasing the level of vulnerability and increasing the resilience in developed areas.

Chapter 7

Hazard Scenarios in the Denver Region

7.1 Background

As a major city, the Denver Region is a conglomeration of integrated highway systems, bridges, public transportation, railways, electrical lines, water and gas distribution pipes, communication systems, every building type from residential to commercial, and more. Its boundary contains 155 square miles of land consisting of 136 individual census tracts (per 2000 census tract designations). Within the region are over 285,000 households, and a population of 600,158 people (2010 Census data). The inventory provided in HAZUS-MH MR4 for the entire Denver Region shows there are approximately 186,000 buildings within the region with an estimated replacement value of $47.2 billion. Residential housing comprises of 68% of the total regional building value. Furthermore, the number and proximity of critical facilities is highly important in regard to a region's vulnerability. In the Denver Region, there are 14 hospitals, 217 schools, 1 fire station, 17 police stations, and 2 emergency operation facilities. Additionally, there are 8 dams and 74 hazardous material sites. The Denver Region has no major military installations, and no nuclear power plants. In addition, the region contains 958,005 feet (292 kilometers) of highway segments, 426 bridges, and 21,351,706 feet (6,508 kilometers) of pipes (including natural gas, water (potable and waste), and crude and refined oil) (HAZUS 2010).

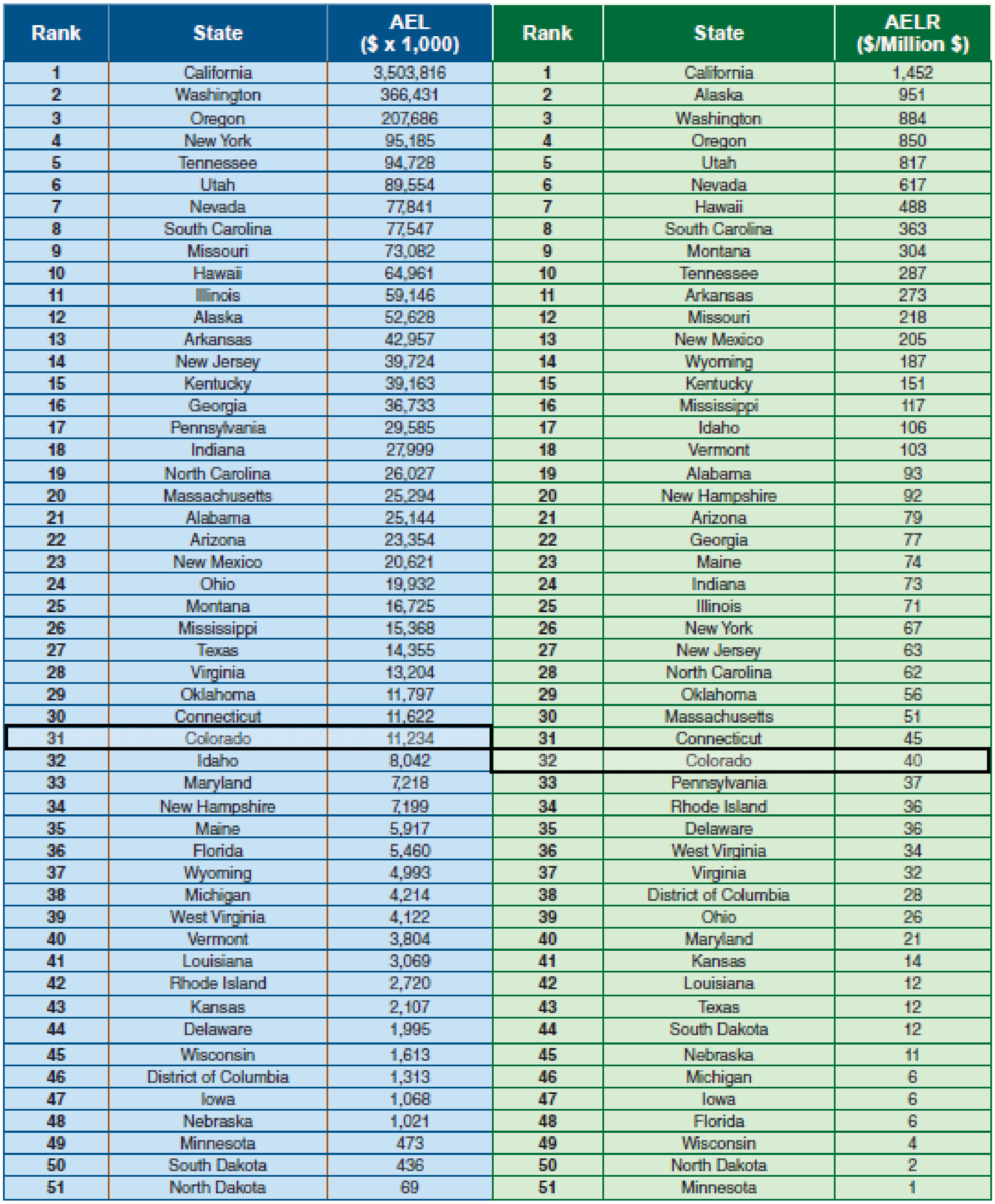
The region has a population growth rate that has "consistently outpaced the national rate every decade since the 1930s", presenting a concern of a concomitant increase in the region's vulnerability (MetroDenver.org 2011). Future plans for Denver are outlined in the Metro Vision 2035 (DRCOG 2010) focusing on inward growth, ultimately increasing the population density, which is effective in promoting efficiency and order, but induces more susceptibility to hazards whether natural, man-made or intentional. Reducing Denver's level of vulnerability to these hazards requires a multi-step process that identifies the individual vulnerabilities within the region and addresses them to mitigate potential damage (both direct and indirect). Several potential stressors identified for the Denver Region were previously described in chapter 6. Understanding the magnitude and behavior of these stressors on a particular study region allows for analysis to be performed showing the likely damage state each would create. Locating the areas where the most damage will occur and where these areas overlap with the locations of critical infrastructure and locations of social vulnerability, sets the stage for planning efforts to be constructed to reduce negative effects, both physical and economical. In this study, the geographical information system (GIS) program, ArcGIS, is used to perform a spatial analysis helpful in understanding and highlighting Denver's vulnerable areas. The following studies examine two specific stressors: an earthquake (a natural hazard), and a set of highway accident scenarios involving the transportation of hazardous materials along a primary corridor through Denver (a man-made hazard). In addition, flooding and population growth recognized as stressors in the Denver Region are briefly investigated.

7.2 Earthquake Hazard

USGS has developed National Seismic Hazard Maps to categorize the seismic design criteria used in the International Building Code (IBC), however, these hazard maps do not accurately represent Colorado as a result of a lack of data used to prepare these maps. According to the 2008 HAZUS MH Estimated Annualized Earthquake Losses (AEL) for the United States, conducted by the Federal Emergency Management Agency (FEMA), the State of Colorado is ranked 31st in the nation based on an annualized earthquake loss of \$11.2 million. The AEL was calculated by "multiplying losses from eight potential ground motions by their respective annual frequencies of occurrence, and then summing the values" (FEMA 2008).

The same national risk assessment was performed by FEMA in 2000, indicating an annualized earthquake loss for the state of Colorado of \$5.8 million, only about half of the 2008 estimate. This discrepancy demonstrates the continuing economic growth in Colorado, as well as an increase in seismic research unveiling more risk in the Great Plains than previously recognized. This change is reflected in the difference between the 1996 USGS Probabilistic Hazard Data and the 2002 USGS Probabilistic Maps.

Figure 7.0 below, from the 2008 FEMA report (FEMA 2008), shows where Colorado is ranked amongst all the other states of the nation by annualized earthquake loss and annualized earthquake loss ratios. The annualized earthquake loss ratio (AELR) normalizes monetary loss by the building inventory, allowing for regional comparisons. The AELR is a loss-to-value ratio of dollars per million dollars of building inventory exposure (FEMA 2008).



Rank	State	AEL ($ x 1,000)	Rank	State	AELR ($/Million $)
1	California	3,503,816	1	California	1,452
2	Washington	366,431	2	Alaska	951
3	Oregon	207,686	3	Washington	884
4	New York	95,185	4	Oregon	850
5	Tennessee	94,728	5	Utah	817
6	Utah	89,554	6	Nevada	617
7	Nevada	77,841	7	Hawaii	488
8	South Carolina	77,547	8	South Carolina	363
9	Missouri	73,082	9	Montana	304
10	Hawaii	64,961	10	Tennessee	287
11	Illinois	59,146	11	Arkansas	273
12	Alaska	52,628	12	Missouri	218
13	Arkansas	42,957	13	New Mexico	205
14	New Jersey	39,724	14	Wyoming	187
15	Kentucky	39,163	15	Kentucky	151
16	Georgia	36,733	16	Mississippi	117
17	Pennsylvania	29,585	17	Idaho	106
18	Indiana	27,999	18	Vermont	103
19	North Carolina	26,027	19	Alabama	93
20	Massachusetts	25,294	20	New Hampshire	92
21	Alabama	25,144	21	Arizona	79
22	Arizona	23,354	22	Georgia	77
23	New Mexico	20,621	23	Maine	74
24	Ohio	19,932	24	Indiana	73
25	Montana	16,725	25	Illinois	71
26	Mississippi	15,368	26	New York	67
27	Texas	14,355	27	New Jersey	63
28	Virginia	13,204	28	North Carolina	62
29	Oklahoma	11,797	29	Oklahoma	56
30	Connecticut	11,622	30	Massachusetts	51
31	Colorado	11,234	31	Connecticut	45
32	Idaho	8,042	32	Colorado	40
33	Maryland	7,218	33	Pennsylvania	37
34	New Hampshire	7,199	34	Rhode Island	36
35	Maine	5,917	35	Delaware	36
36	Florida	5,460	36	West Virginia	34
37	Wyoming	4,993	37	Virginia	32
38	Michigan	4,214	38	District of Columbia	28
39	West Virginia	4,122	39	Ohio	26
40	Vermont	3,804	40	Maryland	21
41	Louisiana	3,069	41	Kansas	14
42	Rhode Island	2,720	42	Louisiana	12
43	Kansas	2,107	43	Texas	12
44	Delaware	1,995	44	South Dakota	12
45	Wisconsin	1,613	45	Nebraska	11
46	District of Columbia	1,313	46	Michigan	6
47	Iowa	1,068	47	Iowa	6
48	Nebraska	1,021	48	Florida	6
49	Minnesota	473	49	Wisconsin	4
50	South Dakota	436	50	North Dakota	2
51	North Dakota	69	51	Minnesota	1

Figure 7.1: Ranking of states by annualized earthquake loss (AEL) and annualized earthquake loss ratios (AELR), provided by FEMA April 2008 HAZUS MH estimated annualized earthquake losses for the United States

Each of these rankings was determined using the 2002 updates to the USGS National Seismic Map in the program HAZUS-MH, which does not provide a fully accurate representation of Colorado's seismic activity. The 2002 USGS National Seismic Map provides information regarding probabilistic ground motions, including the peak ground acceleration and 0.2 second and 1.0 second spectral accelerations with 10% and 2% probabilities of exceedance in 50 years. A few of the factors used in determining these maps include historical seismicity, fault slip rates, quality factor (the ability of the lithosphere to attenuate seismic waves), and site amplification (Matthews 2003). In Colorado, there are approximately 350 known faults, and only three are documented enough to be included in the 2002 USGS National Seismic Map. The other faults are not on these maps solely because trenching and documentation showing minimum slip rates have not been sufficient to qualify for the seismic maps (per conversation with state geologist, Vincent Matthews, April 21st 2011). Therefore, the existing seismic hazard maps are insufficient for the State of Colorado, resulting in an underestimation in the potential losses.

HAZUS-MH is designed to perform two types of risk analysis: probabilistic and scenario. The scenario type is also known as a deterministic analysis, described in chapter 5. This method was chosen to analyze the damage state for the Denver Region, which could be caused by two potential earthquakes, one with the epicenter located at the Rocky Mountain Arsenal Fault, and the other at the Golden Fault Line. By simulating these scenario-based earthquakes, instead of using a probabilistic approach, a more a more effective description could be developed to help aid state and local agencies in mitigation planning and emergency response. Each of these two scenarios is described in detail below, including both the input parameters used for each earthquake, and the resulting effects (both physical and economic) from each seismic event.

7.2.1 Rocky Mountain Arsenal Earthquake

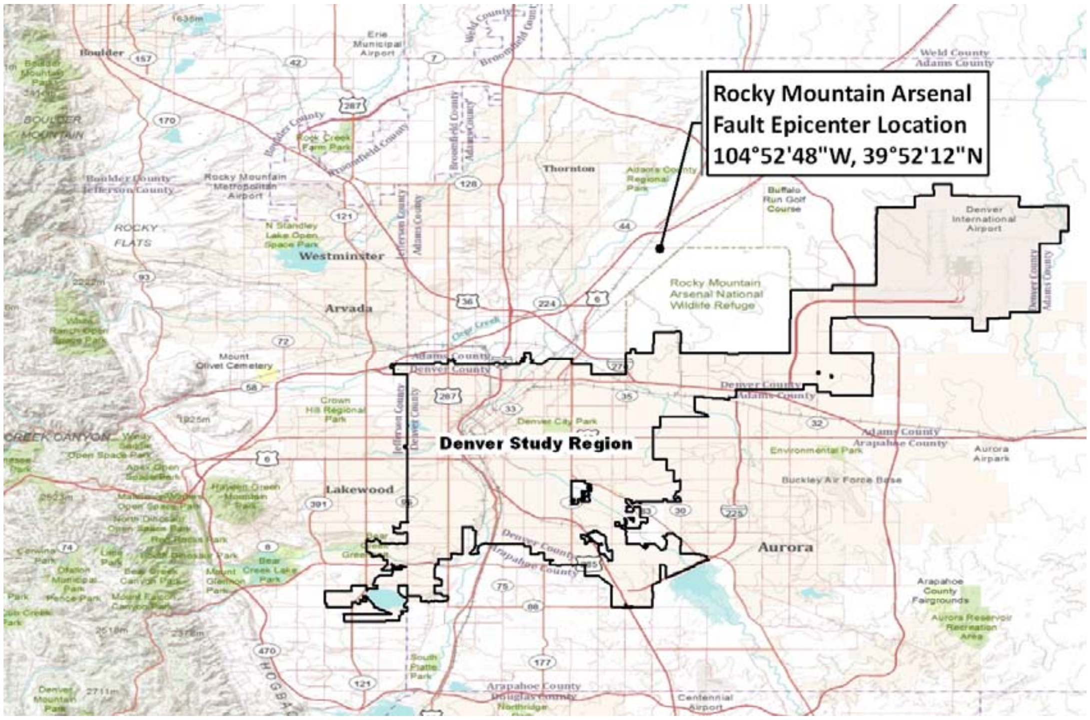


Figure 7.2: Epicenter location of Rocky Mountain Arsenal earthquake scenario

The Rocky Mountain Arsenal seismic behavior is unique because the seismic forces resulted from injecting pressurized fluids into the subsurface as a means of disposing wastes produced by Shell Chemical Company in 1961. The fluids were injected at a rate of 21 million liters per month, and a month after the injections were initiated, two seismographic stations near the area detected several earthquakes to the northeast of Denver. Connections between the abnormal seismic behaviors in the area and the fluid injections were not made until 1965, when geologist David Evans determined this correlation (Harvey 1997). A year and a half after the fluid injections had ceased, the strongest shock felt in Denver, at a magnitude 5.3, occurred on August 9, 1967 at 6:25 in the morning (USGS 2011). The epicenter of the specific earthquake event was used in this study, along with the depth, rupture length, and rupture orientation. The earthquakes induced by the fluid injections resulted in a strike-slip motion (shown in figure 7.2), which was used as the fault type in the HAZUS-MH input (Marz 2005). For both scenarios, the Rocky Mountain Arsenal and the Golden Fault Line, the Maximum Considered Earthquake magnitude was used at a moment magnitude of 6.5. This magnitude is determined by the USGS Quaternary Fault and Fold Database for the Nation. While the Rocky Mountain Arsenal is no longer in operation, the fluid injection revealed the existence of tectonic faults, and accumulating strains could cause future earthquakes associated with these faults.

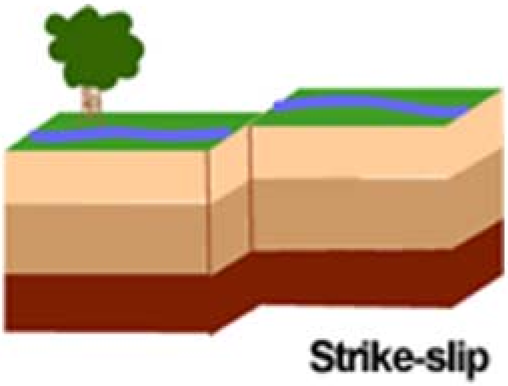


Figure 7.3: Strike-slip fault behavior (provided by earthquake.usgs.gov)

Using a deterministic approach requires several input parameters including: magnitude, epicenter location, depth and width of fault, rupture length and orientation, dip-angle, fault type and the attenuation function. Table 7.1 shows the input parameters used for the Rocky Mountain Arsenal earthquake scenario:

Table 7.1: Input Parameters for Rocky Mountain Arsenal Earthquake Scenario

Rocky Mountain Arsenal Earthquake HAZUS-MH Input Parameters	
moment magnitude	6.5
longitude of epicenter	-104.88
latitude of epicenter	39.87
depth (Km)	10
width(Km)	10
rupture length (sub surface) (Km)	28.8403
rupture length (surface) (Km)	18.197
rupture orientation (degrees)	0 º
dip-angle	90º
attenuation function	WUS Shallow Crustal Event – Extensional
fault type	Strike-slip

The magnitude of ground shaking from an earthquake changes depending on the attenuation function. An appropriate attenuation function for Colorado is currently unknown because the Colorado area lies in between the attenuation functions used for the Western United States (WUS) and for the Central United States (CEUS) (as shown below in figure 7.4) requiring further investigation (HAZUS 2010). In the WUS region, the attenuation is greater than in the CEUS (DOLA 2007). This means that the effects of an earthquake using the WUS attenuation equations will be felt over a smaller geographical extent than with the CEUS model.

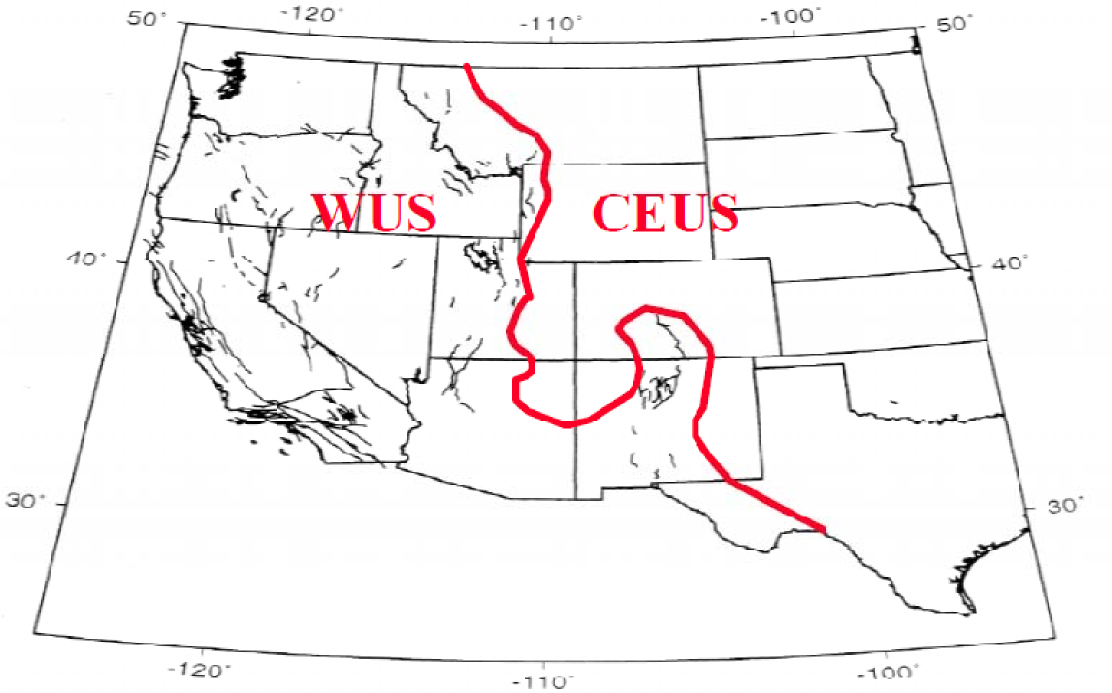


Figure 7.4: HAZUS-MH MR4 map defining Western United States (WUS) and Central United States (CEUS) attenuation zones (provided by pubs.usgs.gov)

HAZUS-MH automatically defaults to the WUS attenuation zone for the Denver Region, which is used in this study. Through conversation, according to state geologist, Vincent Matthews, May 10th, 2011, a Central Eastern United States attenuation function for Colorado is more appropriate, although there are still some who argue toward using an attenuation function from the WUS zone. Using an attenuation function from the WUS zone reduces the amount of damage compared to one from the CEUS zone, underestimating the resulting figures. Also through conversation, Professor Anne Sheehan, May 11th, 2011 from the Department of Geological Sciences and CIRES, University of Colorado at Boulder, expressed that Denver and the High Plains are between the WUS and CEUS zones, and that USArray recently came through Colorado to place a more dense network of seismic stations to record seismic waves to help determine a more exact attenuation function to be used in representing the Denver Region. Before 2002, Colorado only had two seismographs, one of which did not work properly, creating difficulty in detecting smaller earthquakes (Matthews 2003). The data collected from the new stations will be valuable in understanding Colorado's seismic behavior. For the purpose of this study, the WUS attenuation function is appropriate in displaying where the damage is likely to occur and provide a base monetary loss estimate. The specific WUS attenuation function used for the Rocky Mountain Arsenal earthquake scenario is WUS Shallow Crustal Event - Extensional. This specific attenuation function selection is a combination of several attenuations functions from the WUS zone, also referred to as a "cocktail-based" function based on the fault mechanism in HAZUS (HAZUS 2010).

In addition to the approximation of an attenuation function as a limitation in modeling earthquakes in Colorado in HAZUS-MH, soil type classification is another. Soil type is an important parameter because ground motion amplitude is affected by the type of soil in a given location. For example, softer soils typically amplify lower frequencies within the ground shaking, producing more damage in the region. The soil class assigned for the Denver Region is Site Class D as recommended in the 2000 International Building Code in lieu of geotechnical data. Colorado does not have a thorough compilation of soil types, and therefore HAZUS resorts to this default soil type for all of Colorado. Specific soil maps would yield more accurate results, making it a priority to obtain this type of information.

7.2.2 Rocky Mountain Arsenal Earthquake Scenario Results

The results from both scenarios ran in HAZUS are based on 2000 census data, therefore the population, number of households, and other variables are not as high as current data yields; however the data are still valid for a reasonable representation of the extent of damage resulting from a scenario earthquake. Additionally, the 2010 census data is based on the new census tracts that are dissimilar from the 2000 tracts used in HAZUS, making it difficult to update the population data. The following statistics throughout this section are representative of the values provided by HAZUS-MH MR4, unless otherwise noted.

Casualties and Shelter Requirements:

The number of casualties and displaced households are the most important figures in observing the detrimental effect caused by a disaster. Human lives are invaluable, and locations where the number of casualties and displaced households are high, are locations where mitigation measures should be first taken. In the event of a 6.5 magnitude earthquake located at the Rocky Mountain Arsenal historical epicenter, HAZUS estimated a three different casualty estimates based on the time of day (2:00 AM, 2:00 PM, and 5:00 PM). The 2:00 AM estimate assumes the residential occupancy load is at its maximum. The 2:00 PM estimate considers the industrial sector loads are at a maximum, and the 5:00 PM estimate represents the peak commute time. The casualty estimates for 2:00 AM, 2:00 PM, and 5:00 PM are 153, 453, and 320 respectively. The casualty estimates from HAZUS only include those resulting from structural damage (building damage and bridge collapse) and do not account for injuries caused by fires, flood, hazardous material or other such reasons. Figure 7.5 below displays where these casualties are located based on the worst-case scenario at 2:00 PM.

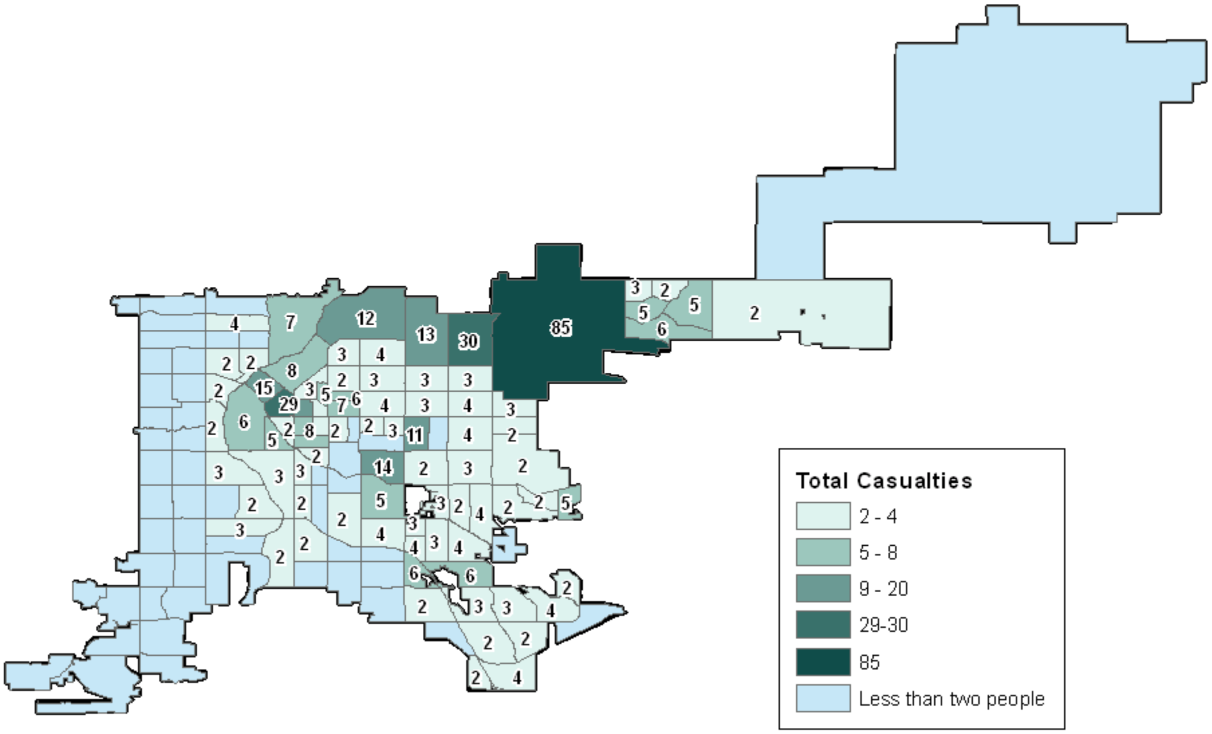


Figure 7.5: Casualties at 2:00 PM due to magnitude 6.5 Rocky Mountain Arsenal earthquake scenario

The above figure shows 85 casualties in the census tract nearest to the epicenter of the earthquake scenario. The tract with the second highest number of casualties is, however, located farther away from the epicenter near the downtown area. Figure 7.6 & 7.7 below, look more closely at the most vulnerable locations in terms of number of casualties.

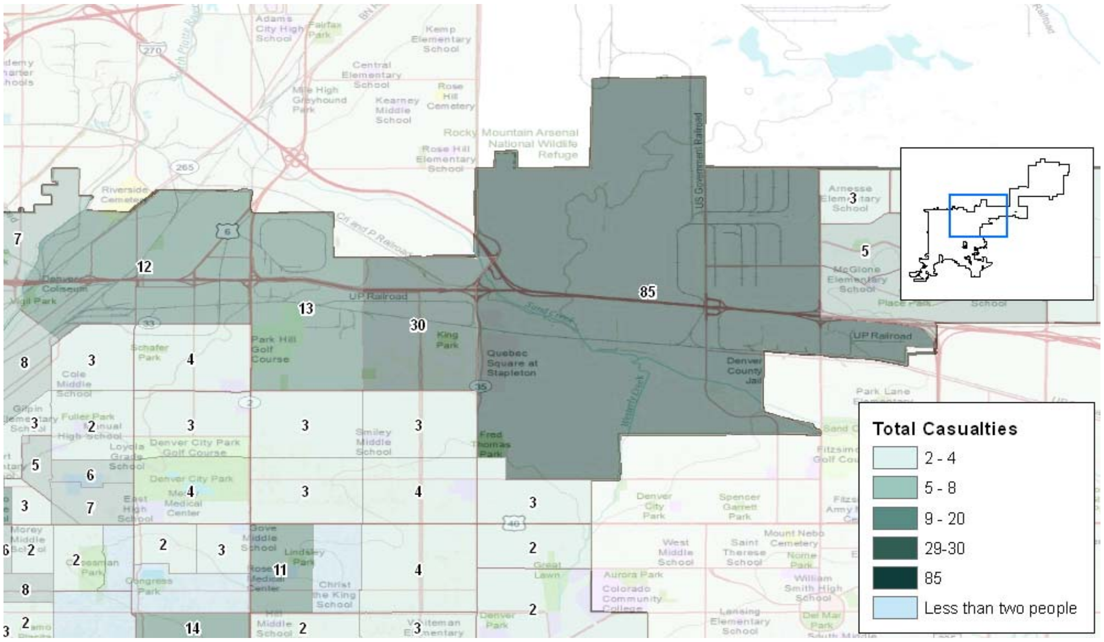


Figure 7.6: Tracts with high casualty numbers nearest to earthquake epicenter

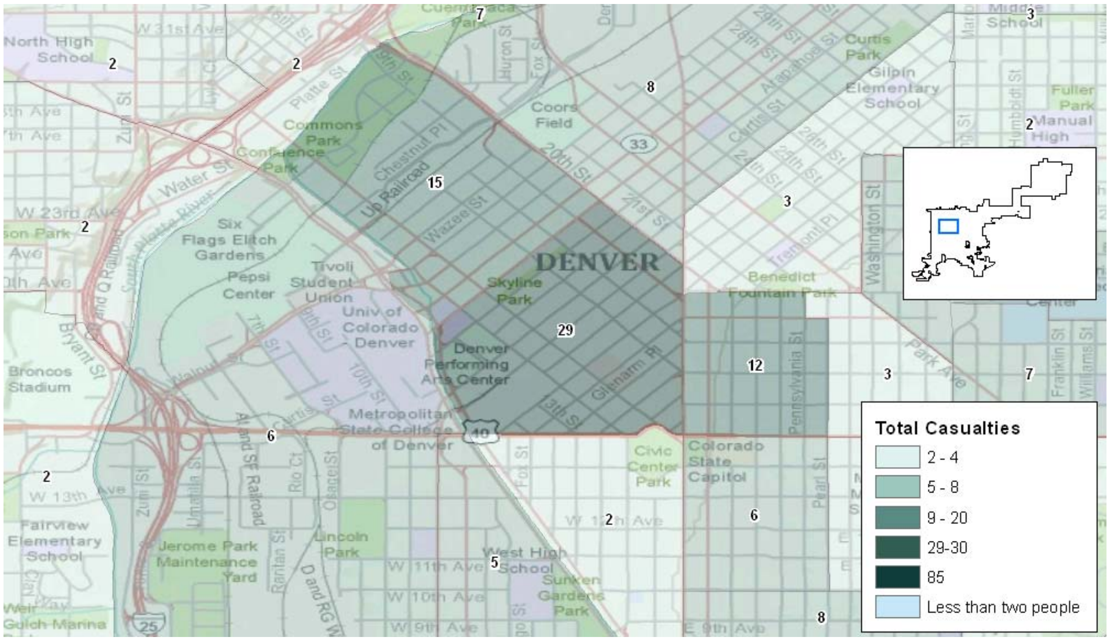


Figure 7.7: Tracts with high casualty numbers near downtown Denver

Predicting the number of short term shelter needs and number of displaced households is essential in emergency response planning. Observing which areas will likely need shelter support is another key identifier in determining which areas are most vulnerable in the case of a hazardous event. In this scenario, HAZUS estimates that there are a total of 13,278 displaced households. 7,955 of these displaced households will require public temporary shelter. These estimated figures can help prepare an inventory of this many beds for this situation or one similar. Currently, mitigation plans for the Denver Region do not expect a magnitude 6.5 earthquake to occur that will cause this many people to require public shelter, and therefore there are likely not enough temporary shelters and beds to support this many people. The number of short term shelter needs and number of displaced households per tract are shown in figures 7.8 & 7.9 below.

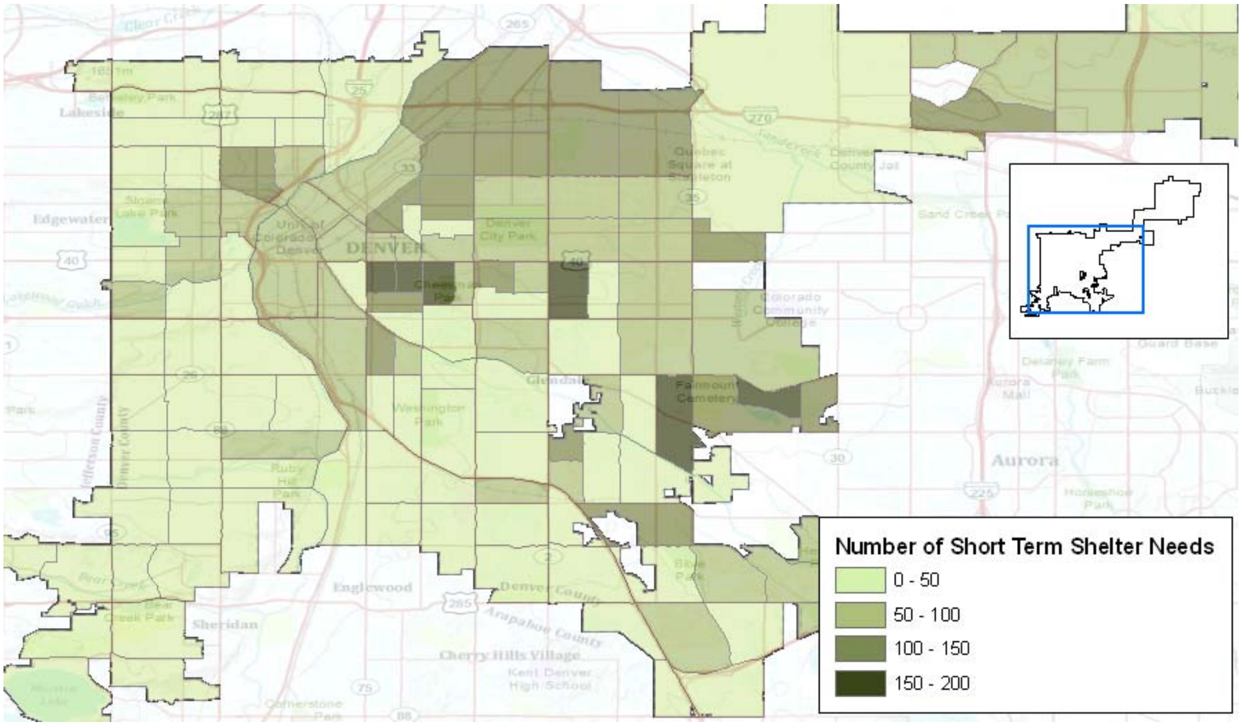


Figure 7.8: Number of short term shelter needs per census tract

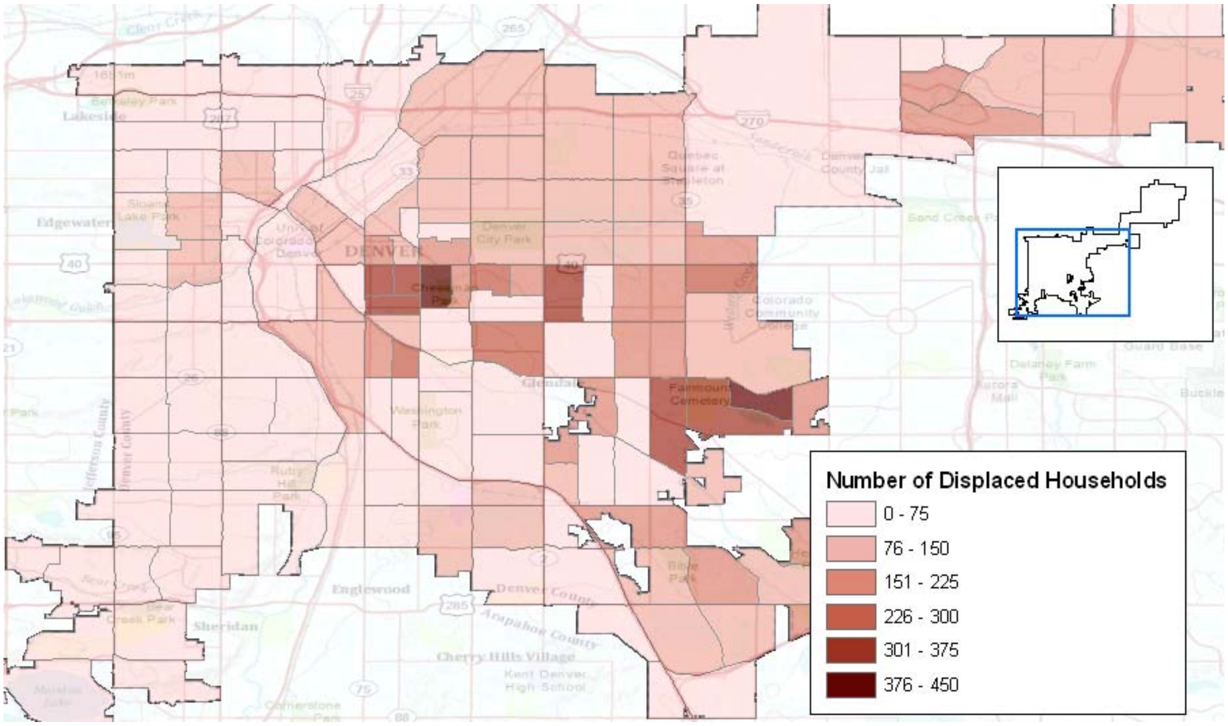
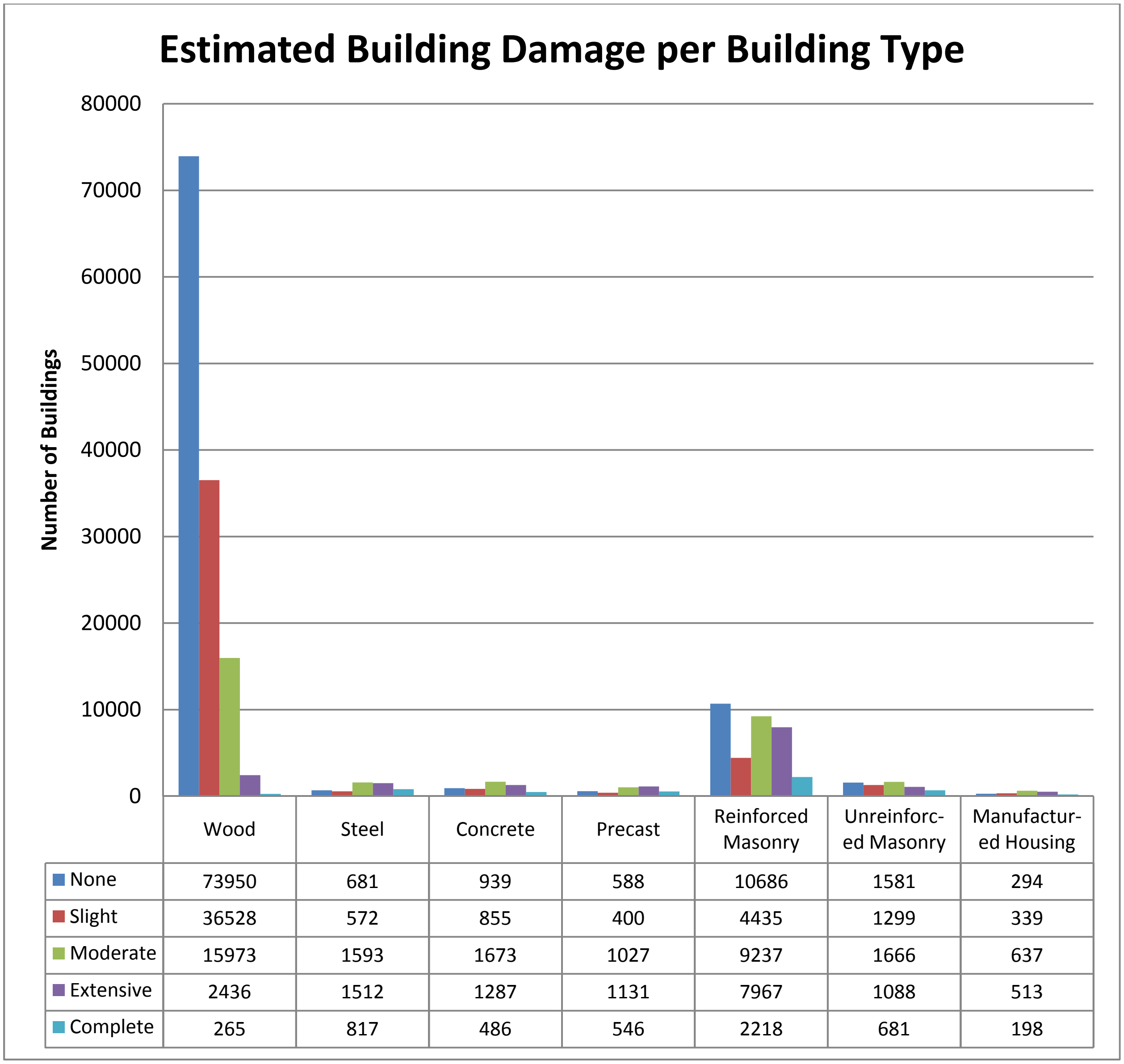


Figure 7.9: Number of displaced households per census tract

Estimated Building Losses:

HAZUS categorizes building damage into four different descriptions: slight, moderate, extensive, and complete. The individual definitions of each category depend on the building material and structure type. The 6.5 magnitude Rocky Mountain Arsenal earthquake caused 52,950 of the total 186,000 buildings in the region to be moderately damaged, and 5,210 damaged beyond repair. Figure 7.10 shows the expected building damage by building type:



	Wood	Steel	Concrete	Precast	Reinforced Masonry	Unreinforc-ed Masonry	Manufactur-ed Housing
None	73950	681	939	588	10686	1581	294
Slight	36528	572	855	400	4435	1299	339
Moderate	15973	1593	1673	1027	9237	1666	637
Extensive	2436	1512	1287	1131	7967	1088	513
Complete	265	817	486	546	2218	681	198

Figure 7.10: Estimated building damage for each building type

Figure 7.10 above shows wood as the primary building type in the Denver Region, followed by reinforced masonry. Determining an itemized inventory of the buildings within a region by building material is important in predicting the damage induced by an earthquake. For example, fires typically occur after an earthquake, therefore if the primary building material used in the region is wood, the amount of damage would likely be higher than if the primary material were steel, masonry, or concrete. As a result of this scenario, HAZUS estimated that the fires as an output of the earthquake will displace a total of 858 people and damage $35,000,000 worth in building value. This figure also shows that the building type with the highest number of buildings completely damaged is un-reinforced masonry based on the percentage of the number of buildings completely destroyed out of the total number of buildings per building type. Therefore, reinforced masonry buildings should be the first building type for retrofit applications, and design codes applicable to reinforced masonry buildings should be re-examined to account for more appropriate seismic forces.

Figures 7.11 & 7.12 below graphically show the building damage losses and total building losses for all building categories combined (educational, government, religion, agriculture, residential, industry, and commercial) within the region. Building damage losses include the estimated costs to repair/replace the building damage as well as its contents. Total building losses incorporate business interruption losses depending on the structure type (including wage, capital-related, rental, relocation, and temporary living expenses for displaced households). Determining the location of where the most building damage occurs can aid emergency response teams as well as provide a basis for resource allocation locations. Additionally, highlighting the areas where the most expected building damage is located provides the public with locations where retrofits should be implemented. Each of the two following figures show extensive damage in the census tract located nearest to the epicenter of the earthquake, but also in the downtown area located near the center of the Denver Region.

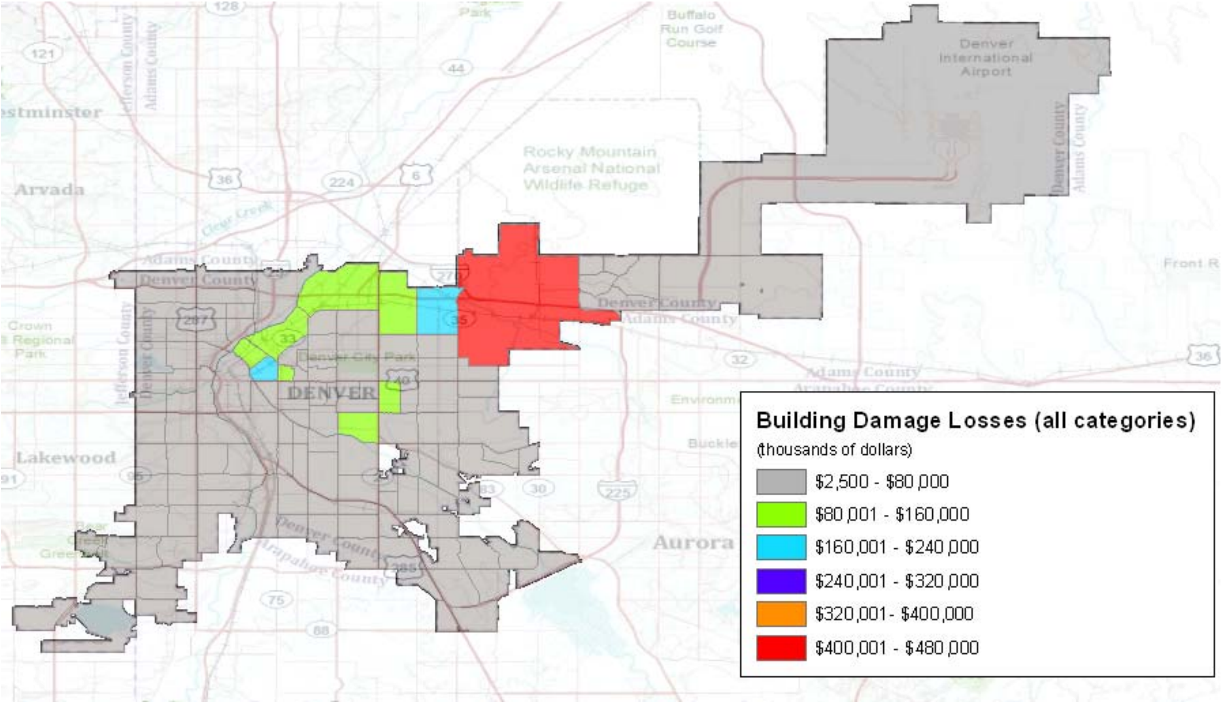


Figure 7.11: Building damage losses for all building type categories as a result of the Rocky Mountain Arsenal earthquake scenario per tract

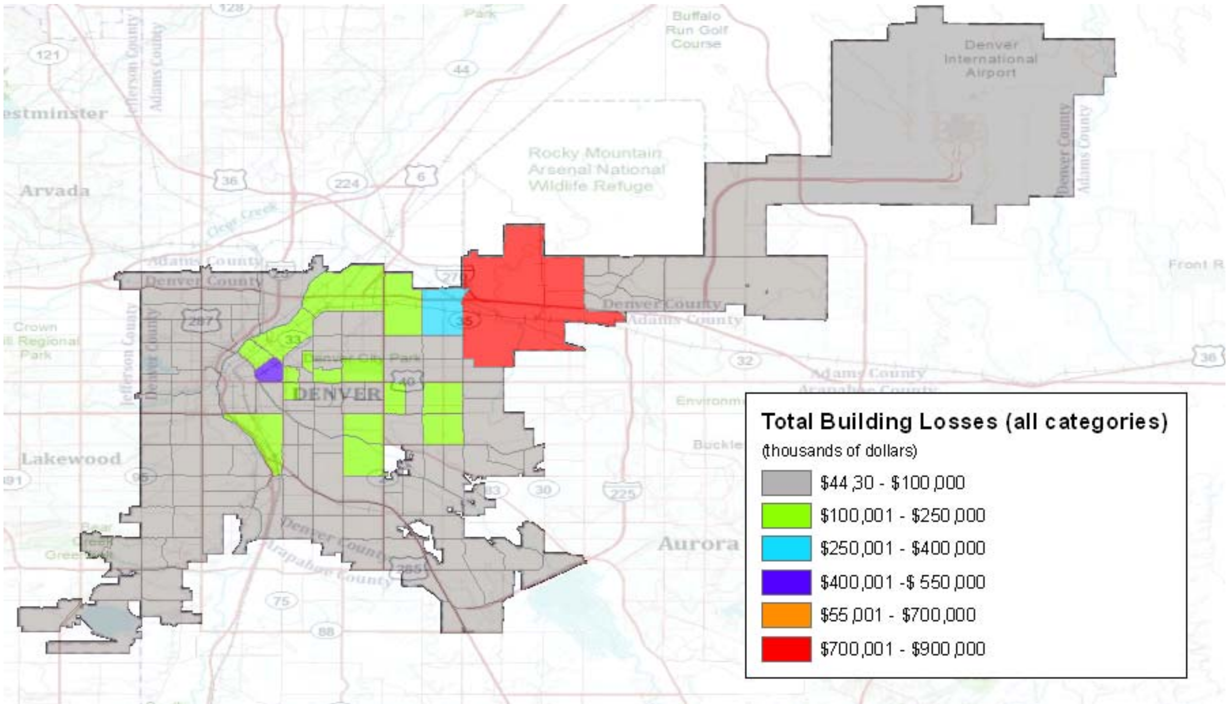
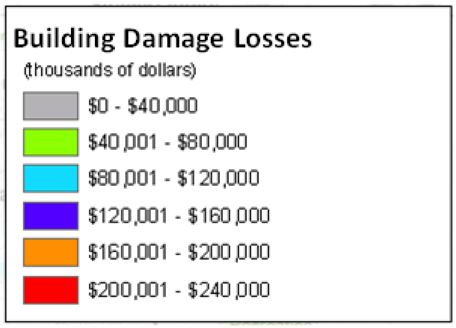


Figure 7.12: Total building losses for all building type categories as a result of the Rocky Mountain Arsenal earthquake scenario per tract

Using the same scale for monetary loss due to building damage and the same scale for total building losses, the building type (by function) experiencing the greatest loss can be graphically determined. Figures 7.13 through 7.27 show that the monetary losses associated with commercial buildings is much higher than all the other building type categories, indicating a need for special code considerations or dispersing commercial buildings to prevent extensive economic damage to the Denver Region in the event of an earthquake.



Building Damage Losses
(thousands of dollars)
⬜ $0 - $40,000
🟩 $40,001 - $80,000
🟦 $80,001 - $120,000
🟪 $120,001 - $160,000
🟧 $160,001 - $200,000
🟥 $200,001 - $240,000

Figure 7.13: Building damage losses scale used for figures 7.14 through 7.20 per census tract

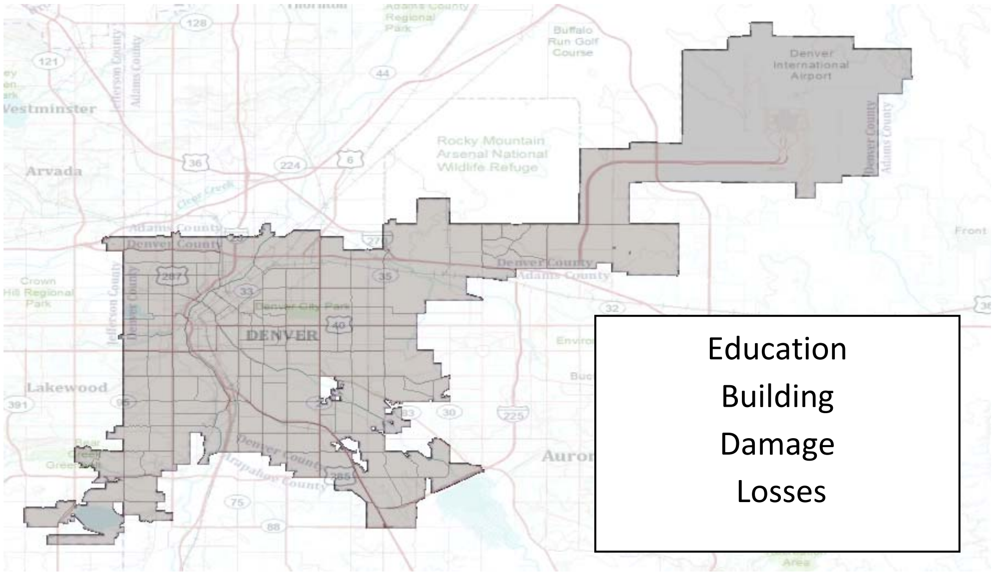


Figure 7.14: Scaled education building damage losses caused by Rocky Mountain Arsenal earthquake scenario

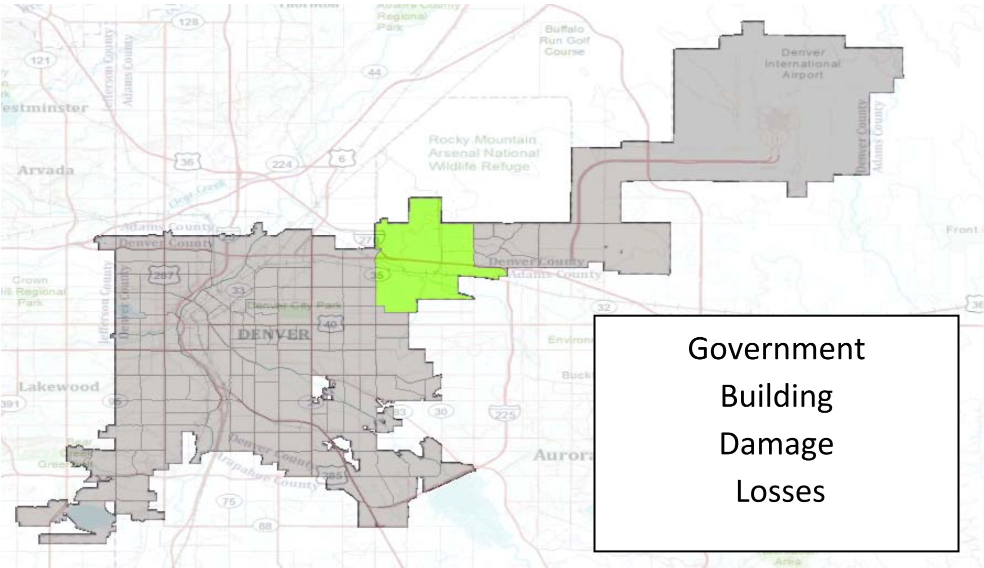


Figure 7.15: Scaled government building damage losses caused by Rocky Mountain Arsenal earthquake scenario

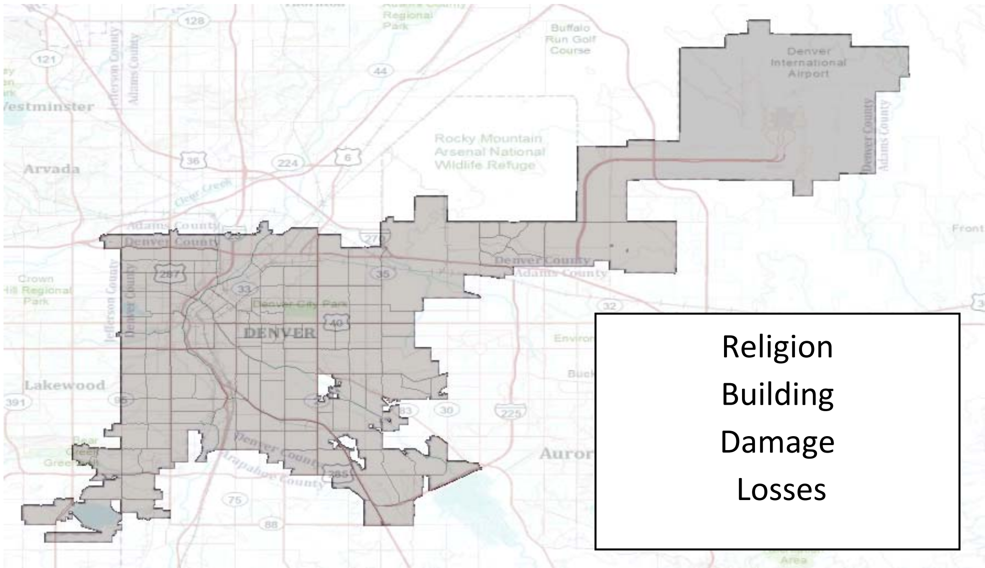


Figure 7.16: Scaled religion building damage losses caused by Rocky Mountain Arsenal earthquake scenario

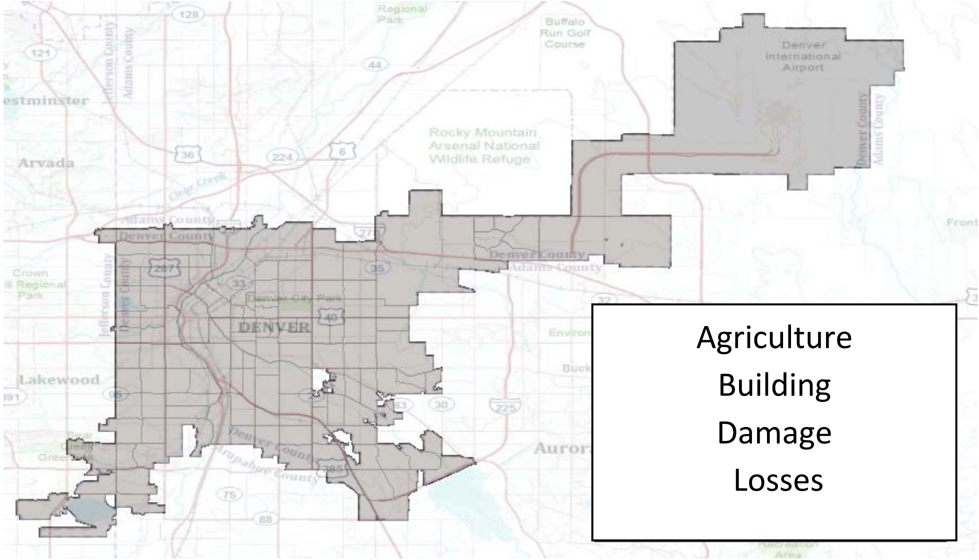


Figure 7.17: Scaled agriculture building damage losses caused by Rocky Mountain Arsenal earthquake scenario

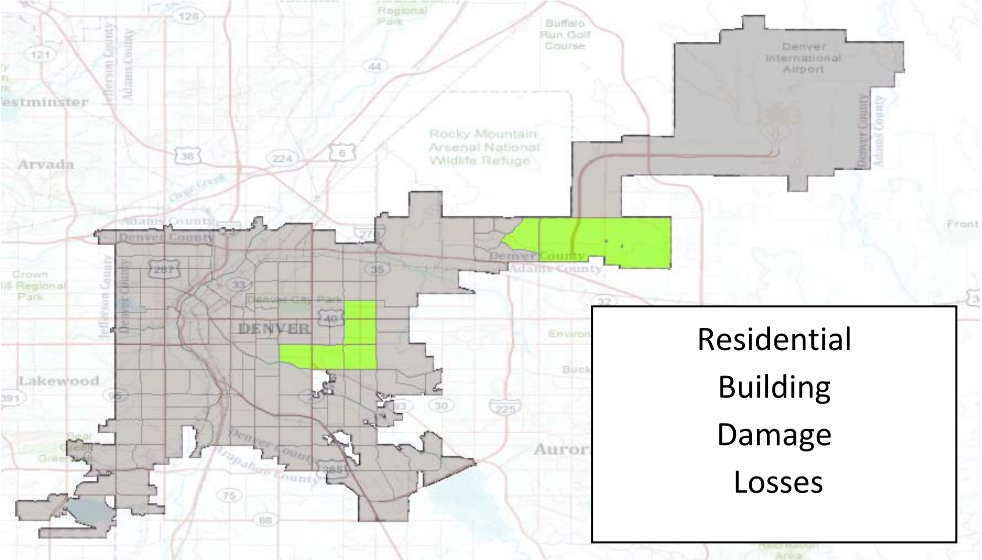


Figure 7.18: Scaled residential building damage losses caused by Rocky Mountain Arsenal earthquake scenario

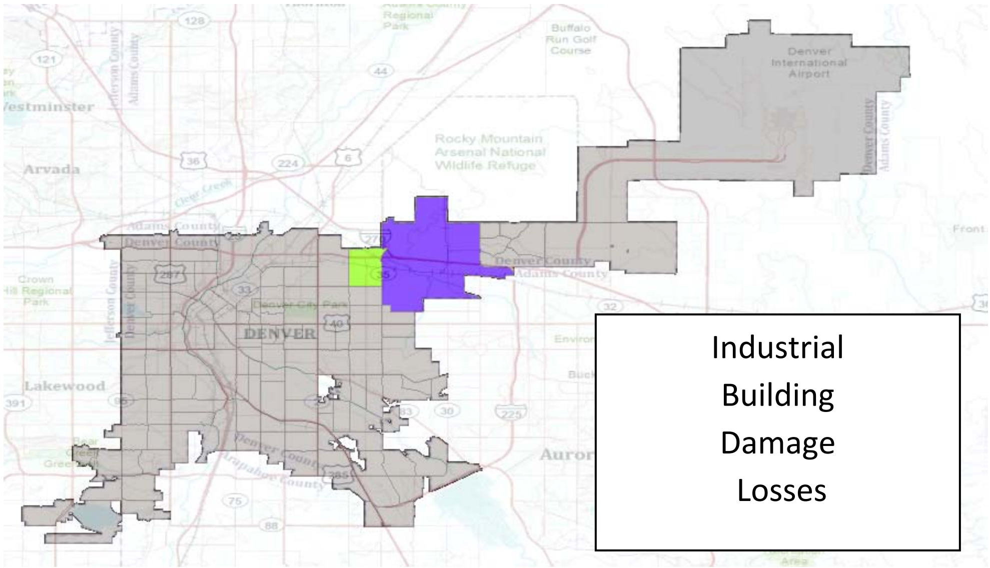


Figure 7.19: Scaled industrial building damage losses caused by Rocky Mountain Arsenal earthquake scenario

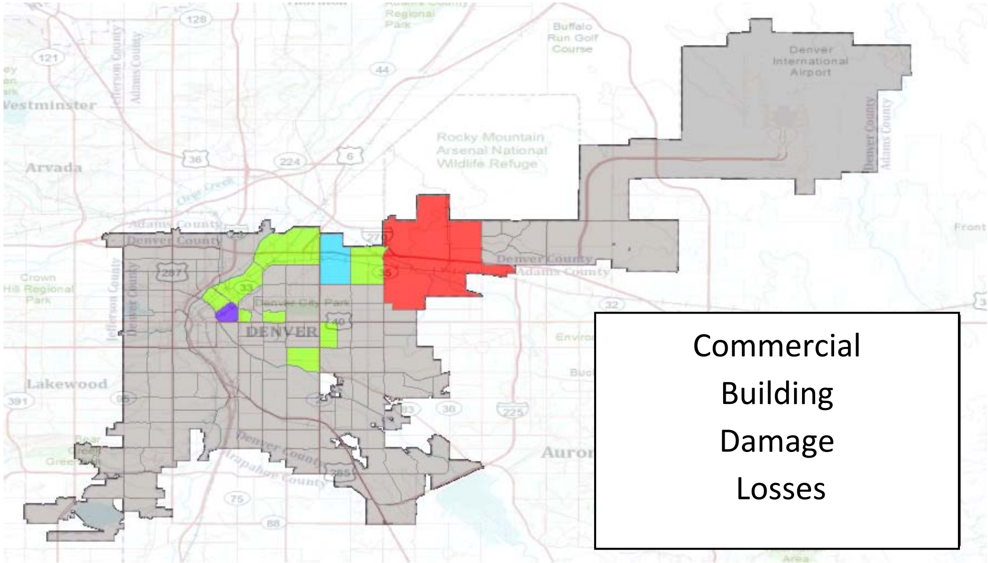
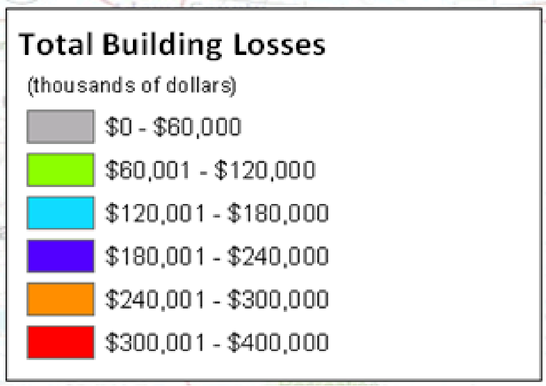


Figure 7.20: Scaled commercial building damage losses caused by Rocky Mountain Arsenal earthquake scenario



Total Building Losses

(thousands of dollars)

⬜	$0 - $60,000
🟩	$60,001 - $120,000
🟦	$120,001 - $180,000
🟪	$180,001 - $240,000
🟧	$240,001 - $300,000
🟥	$300,001 - $400,000

Figure 7.21: Building damage losses scale used for figures 7.22 through 7.27 per census tract

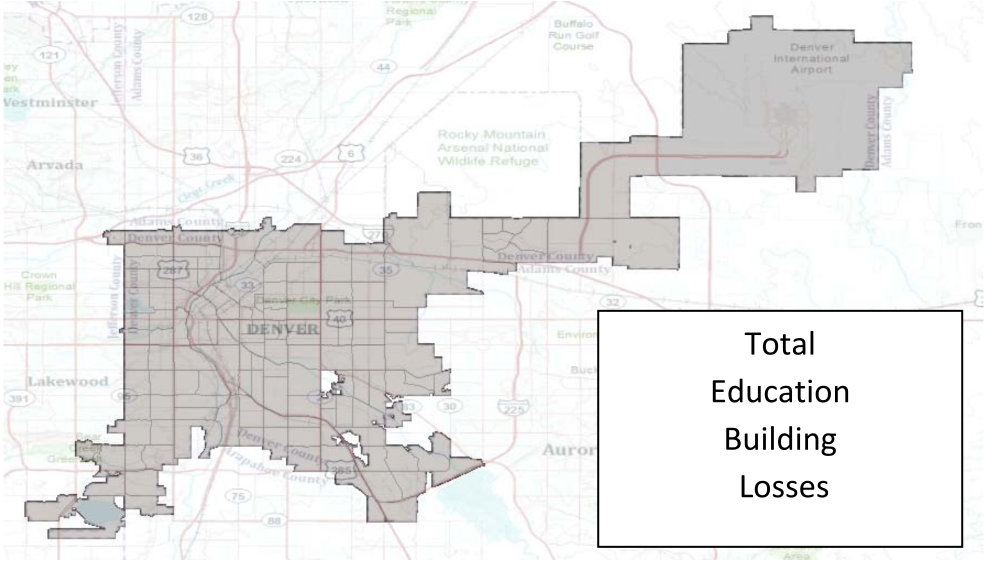


Figure 7.22: Total education building losses caused by Rocky Mountain Arsenal earthquake scenario

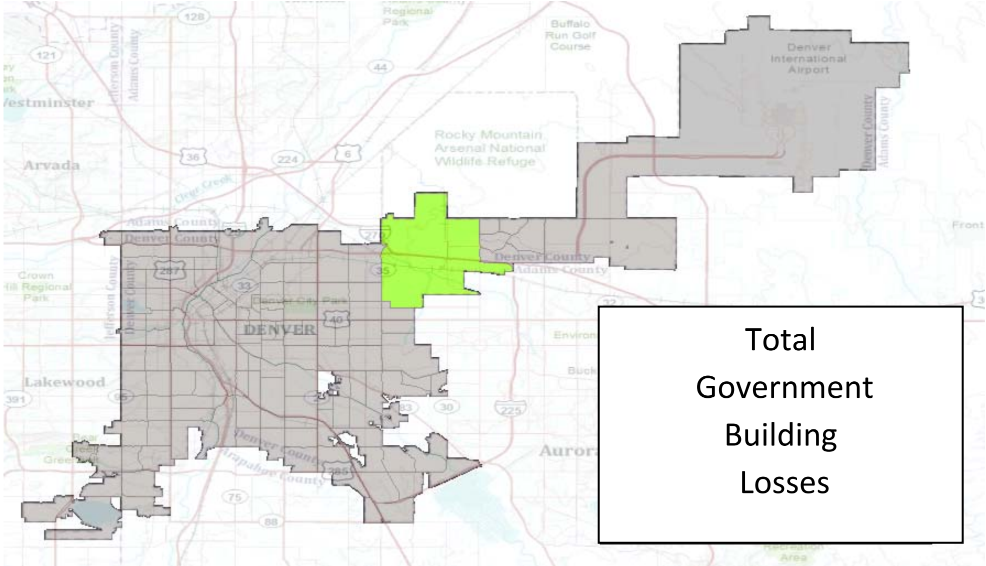


Figure 7.23: Total scaled government building losses caused by Rocky Mountain Arsenal earthquake scenario

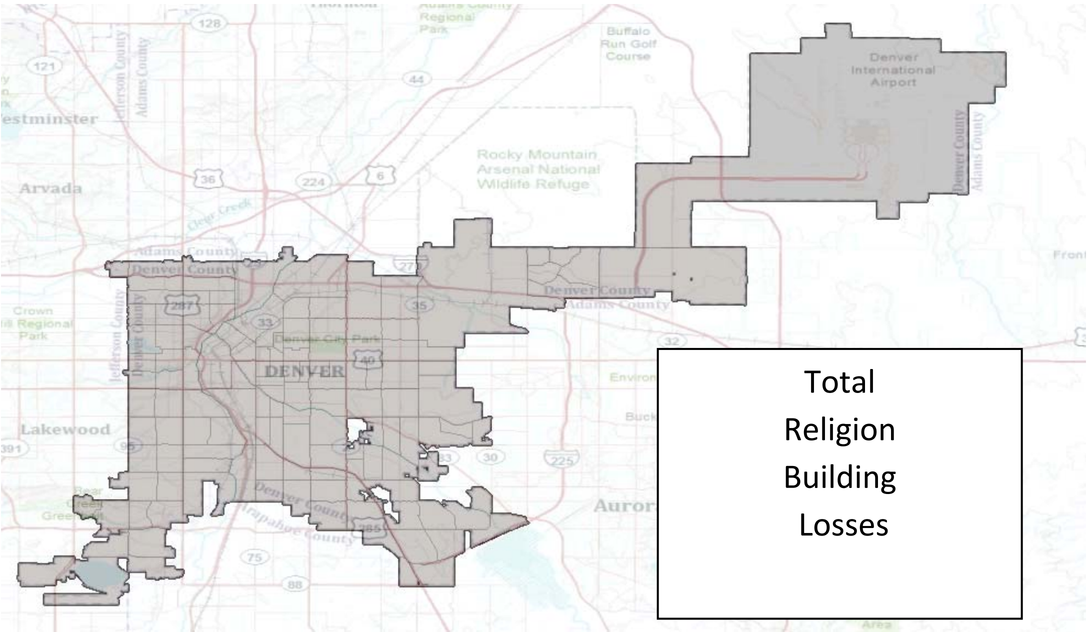


Figure 7.24: Total scaled religion building losses caused by Rocky Mountain Arsenal earthquake scenario

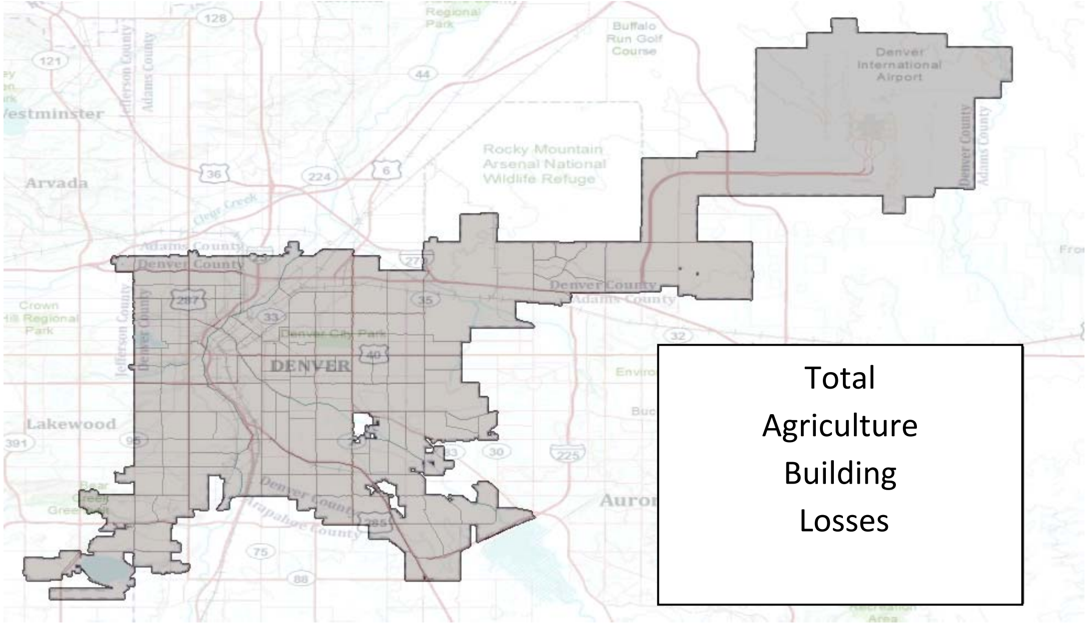


Figure 7.25: Total scaled agriculture building losses caused by Rocky Mountain Arsenal earthquake scenario

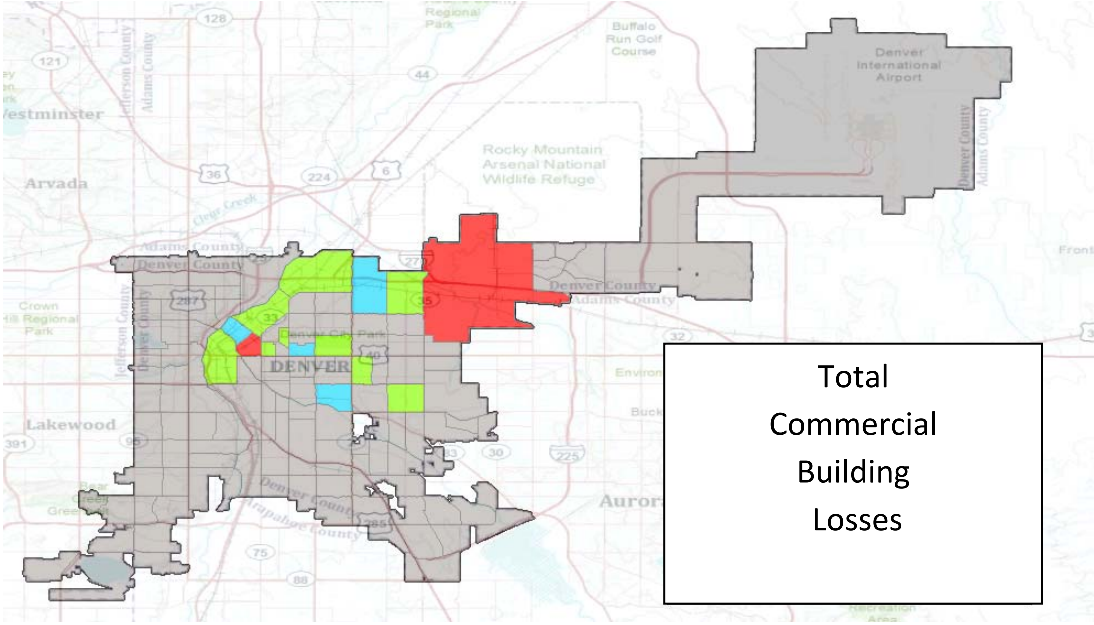


Figure 7.26: Total scaled commercial building losses caused by Rocky Mountain Arsenal earthquake scenario

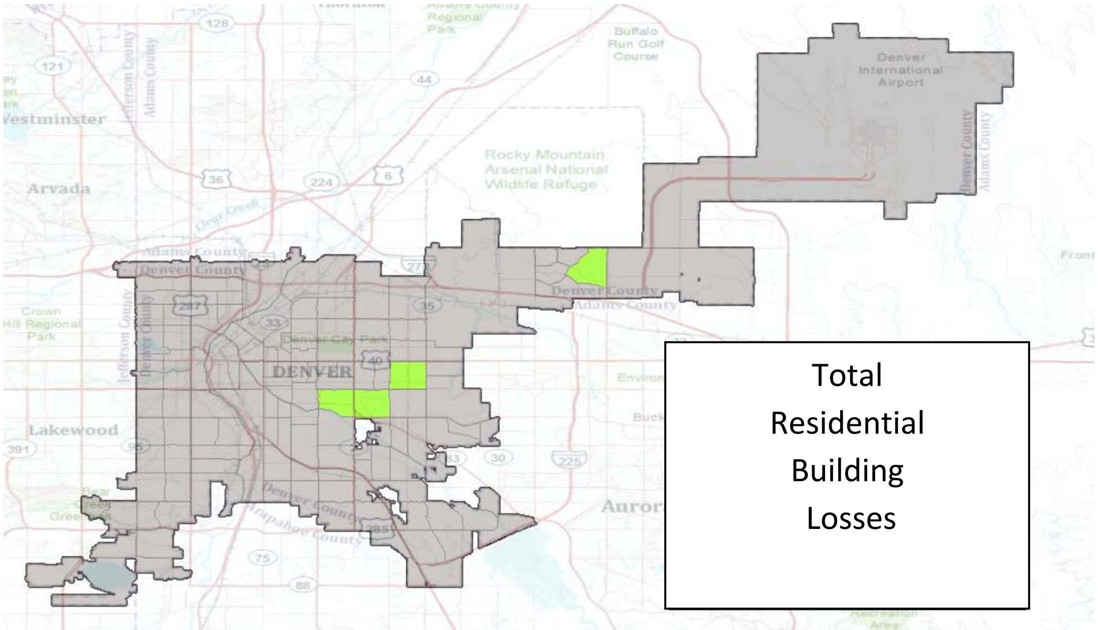


Figure 7.27: Total scaled residential building losses caused by Rocky Mountain Arsenal earthquake scenario

The building losses for each of the building categories mentioned above are individually observed in the following figures 7.28 through 7.40. These figures are scaled individually, providing more specific detail showing where and the extent of monetary losses for each individual sector. For each building category, both the building damage losses and total building losses are adjacently shown for comparison.

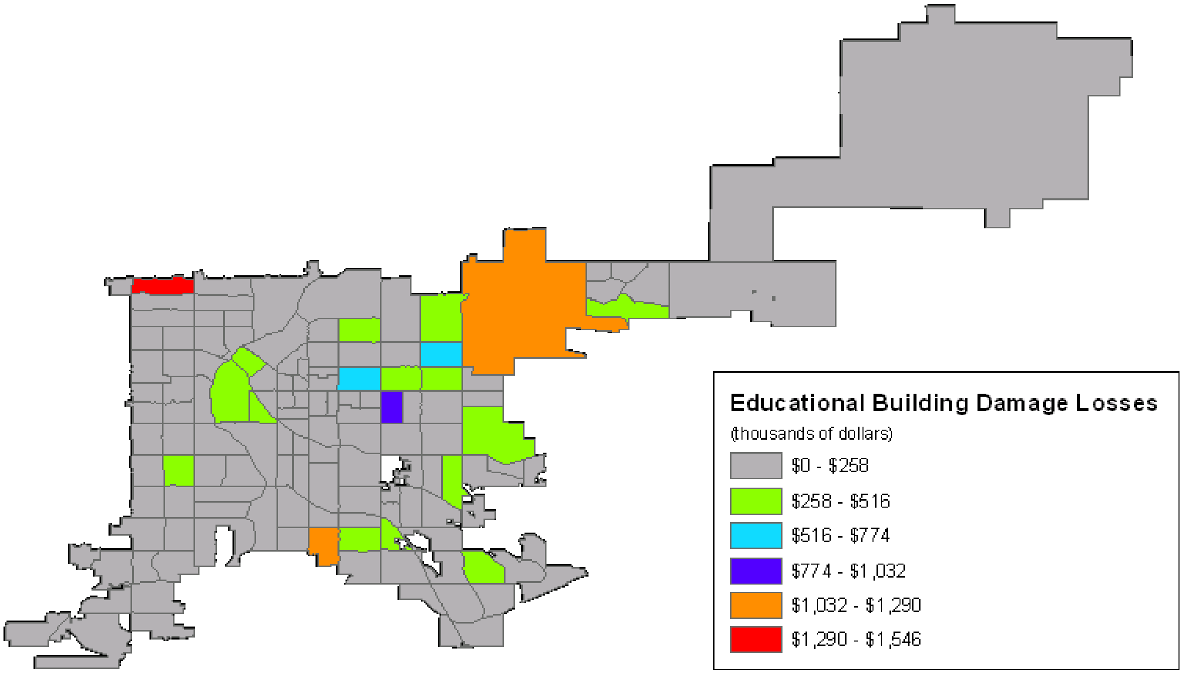


Figure 7.28: Education building damage losses caused by Rocky Mountain Arsenal earthquake scenario

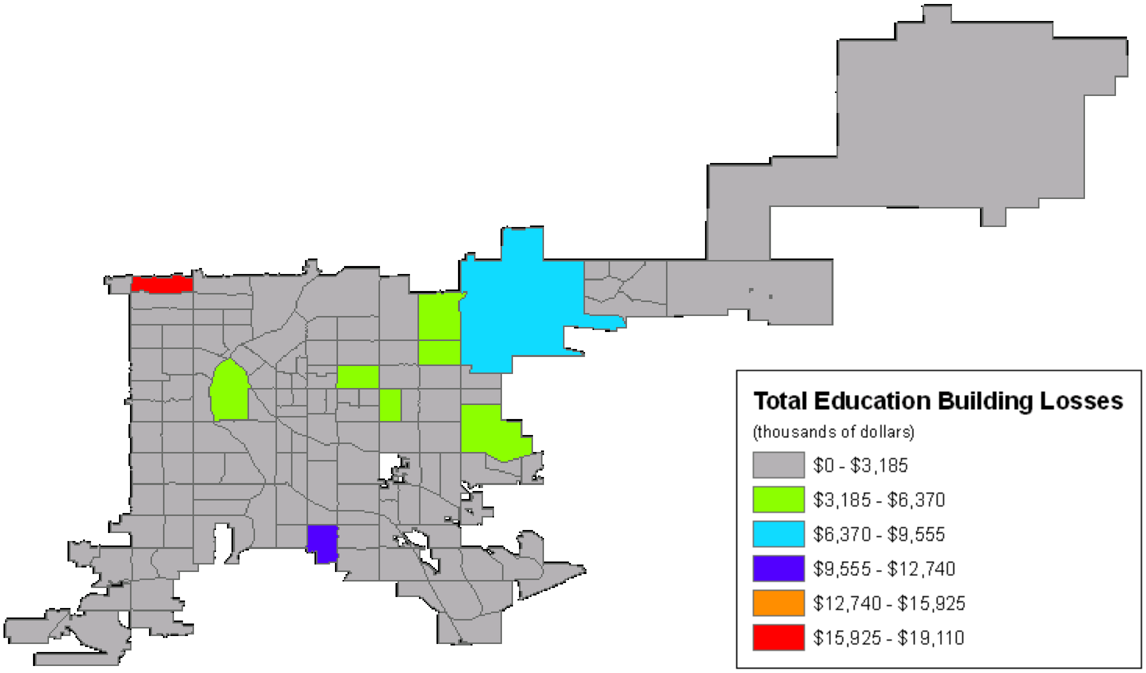


Figure 7.29: Total education building losses caused by Rocky Mountain Arsenal earthquake scenario

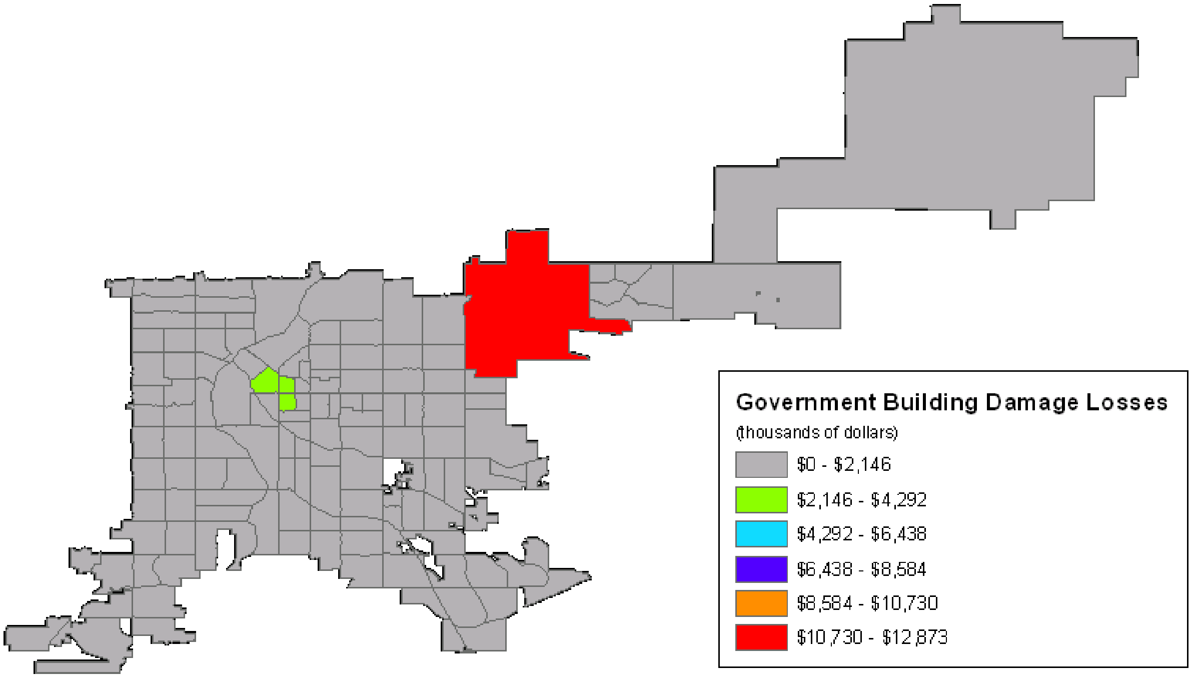


Figure 7.30: Government building damage losses caused by Rocky Mountain Arsenal earthquake scenario

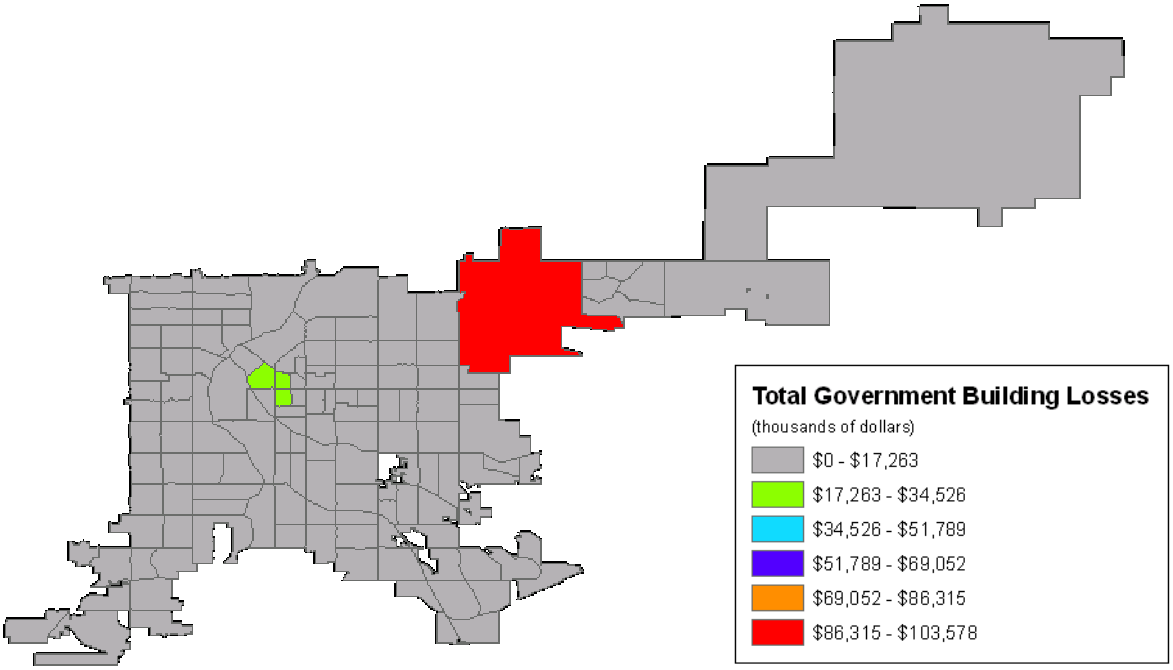


Figure 7.31: Total government building losses caused by Rocky Mountain Arsenal earthquake scenario

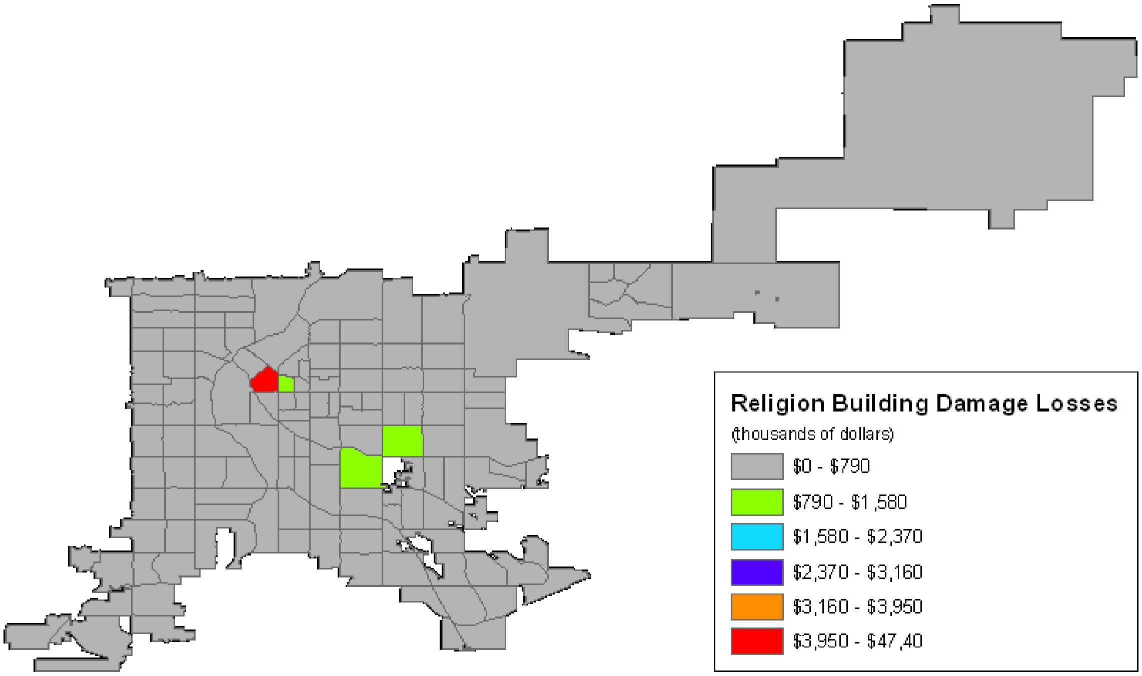


Figure 7.32: Religion building damage losses caused by Rocky Mountain Arsenal earthquake scenario

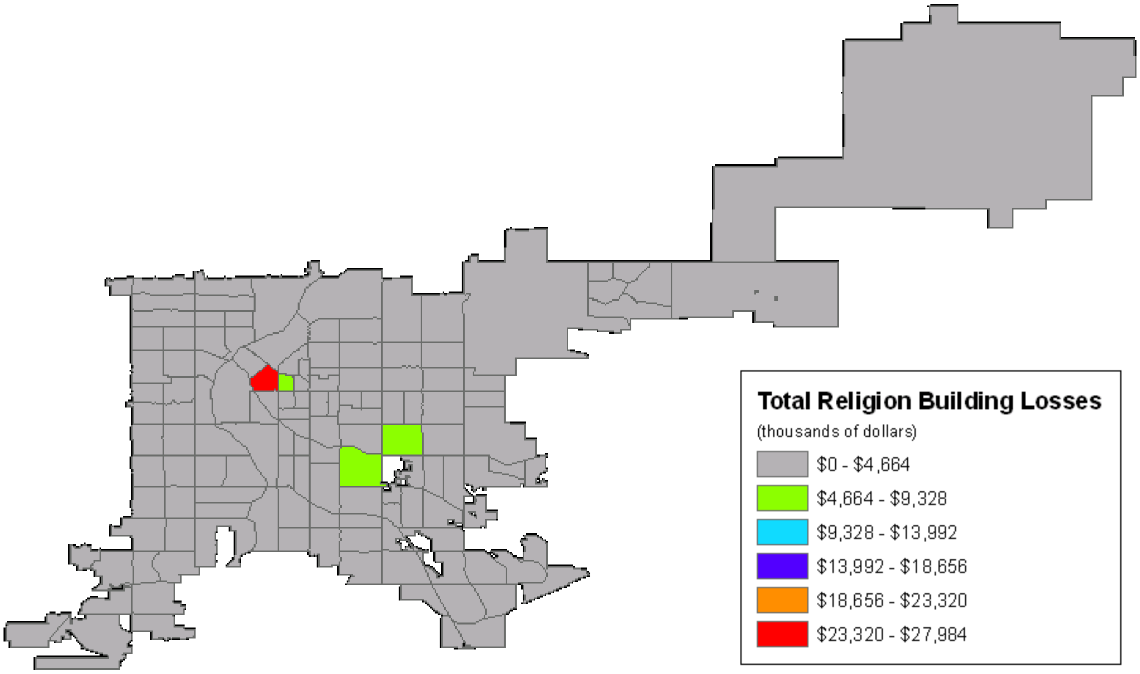


Figure 7.33: Total religion building losses caused by Rocky Mountain Arsenal earthquake scenario

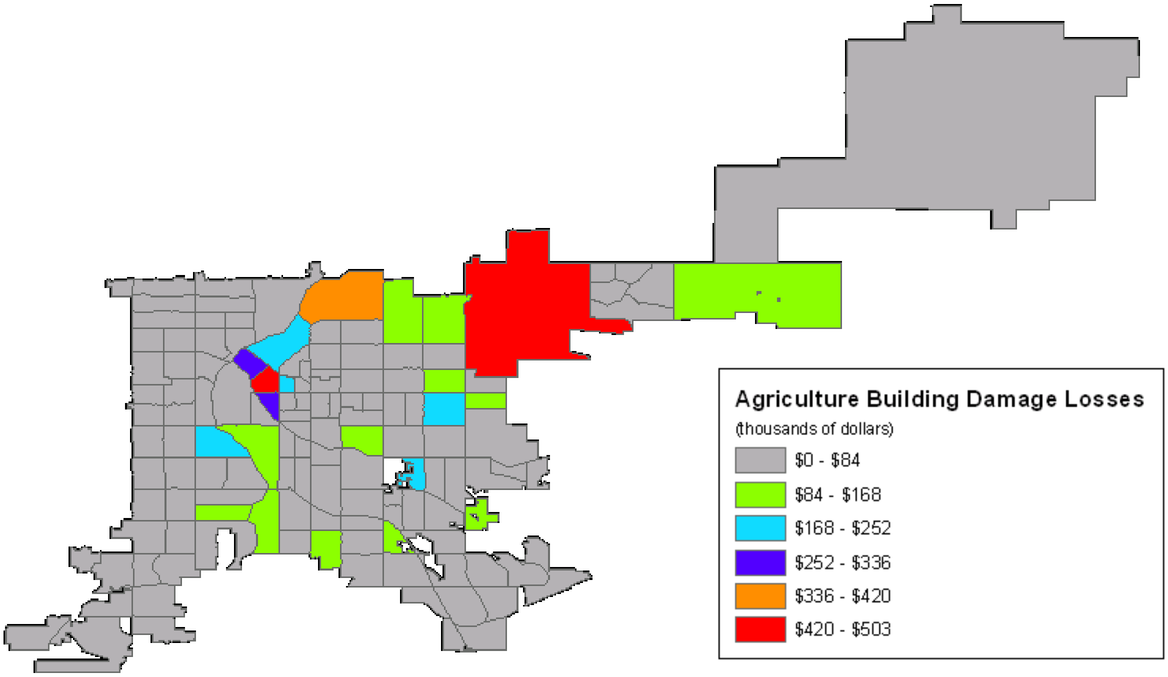


Figure 7.34: Agriculture building damage losses caused by Rocky Mountain Arsenal earthquake scenario

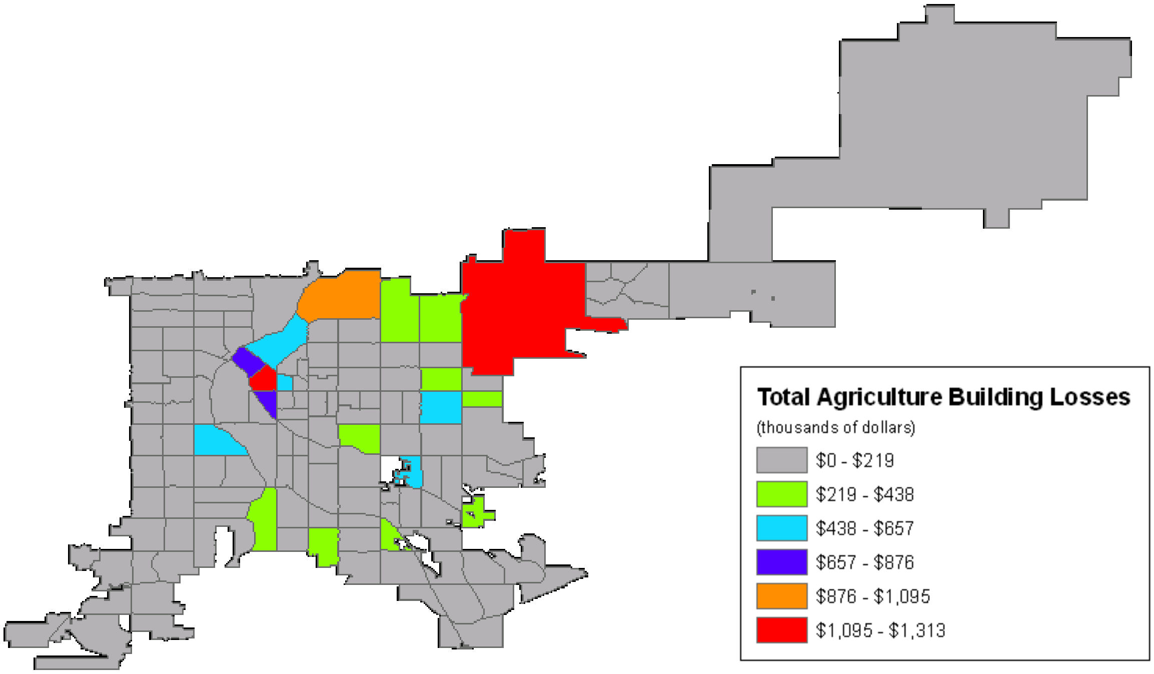


Figure 7.35: Total agriculture building losses caused by Rocky Mountain Arsenal earthquake scenario

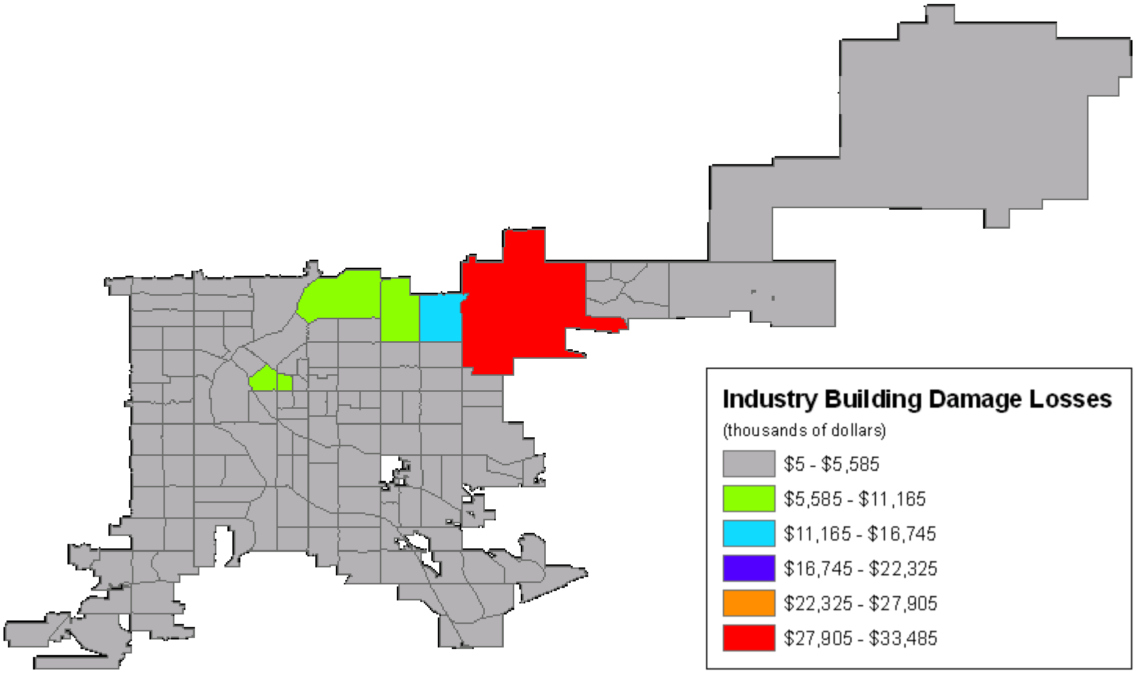


Figure 7.36: Industry building damage losses caused by Rocky Mountain Arsenal earthquake scenario

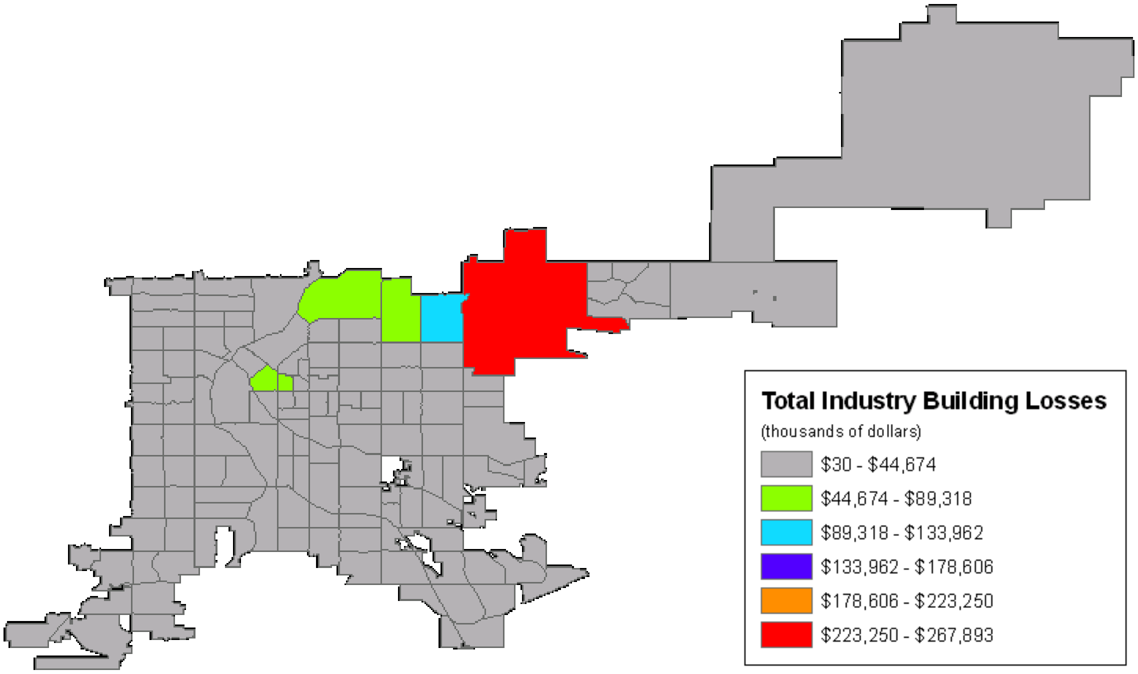


Figure 7.37: Total industry building losses caused by Rocky Mountain Arsenal earthquake scenario

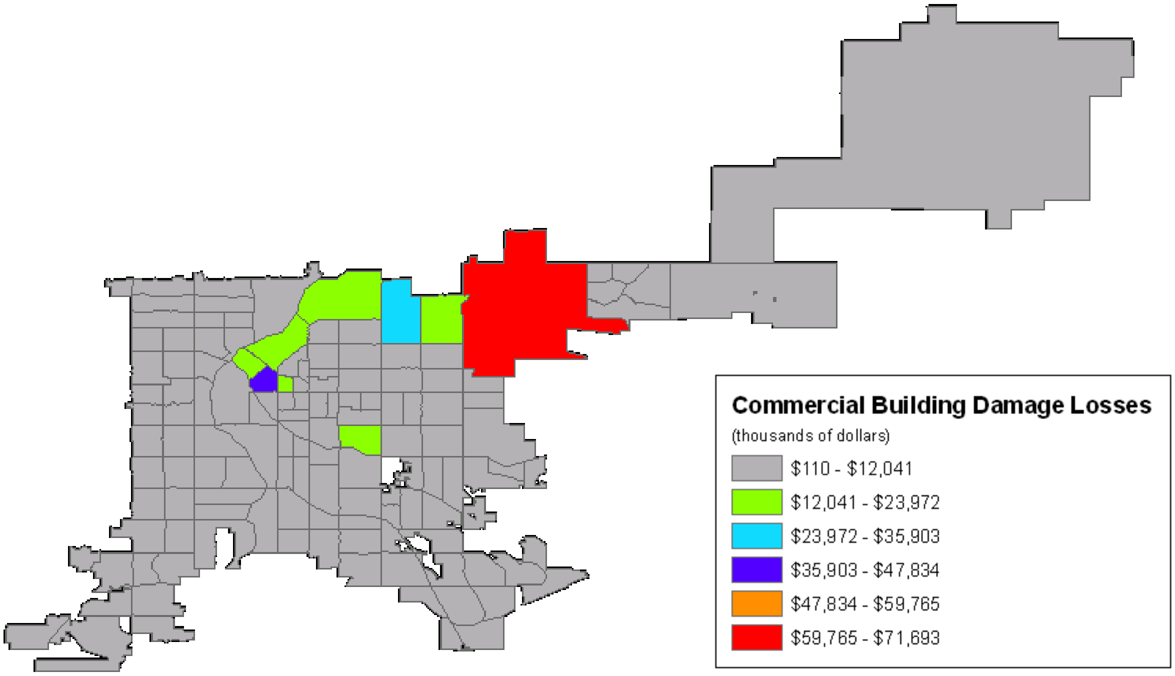


Figure 7.38: Commercial building damage caused by Rocky Mountain Arsenal earthquake scenario

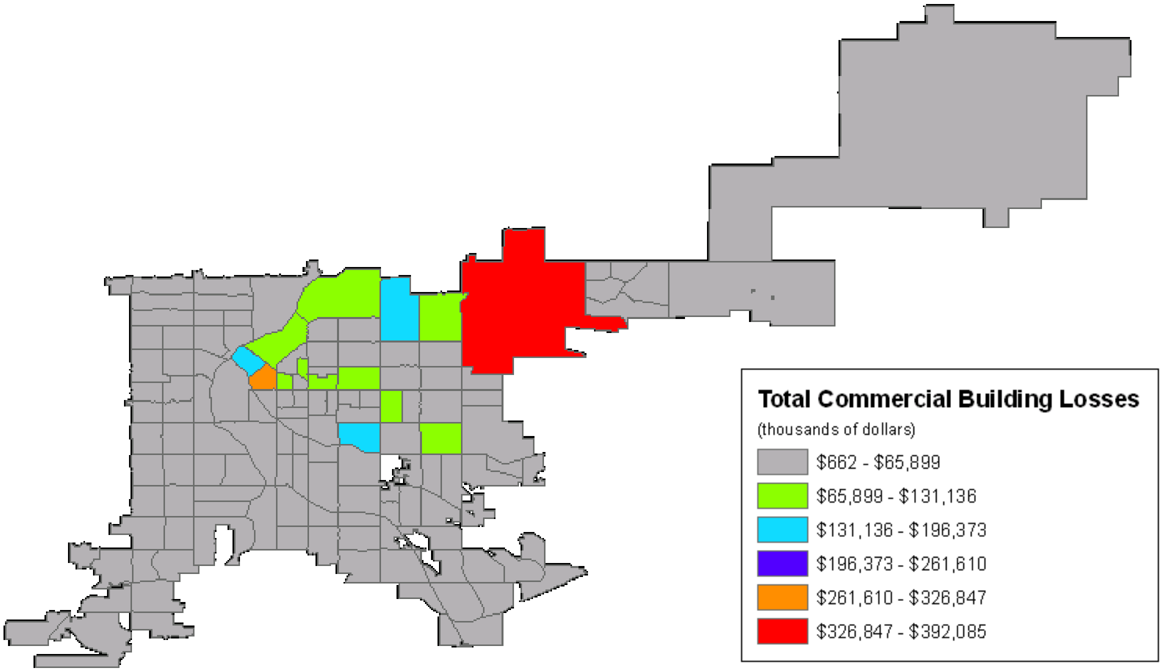


Figure 7.39: Total commercial building losses caused by Rocky Mountain Arsenal earthquake scenario

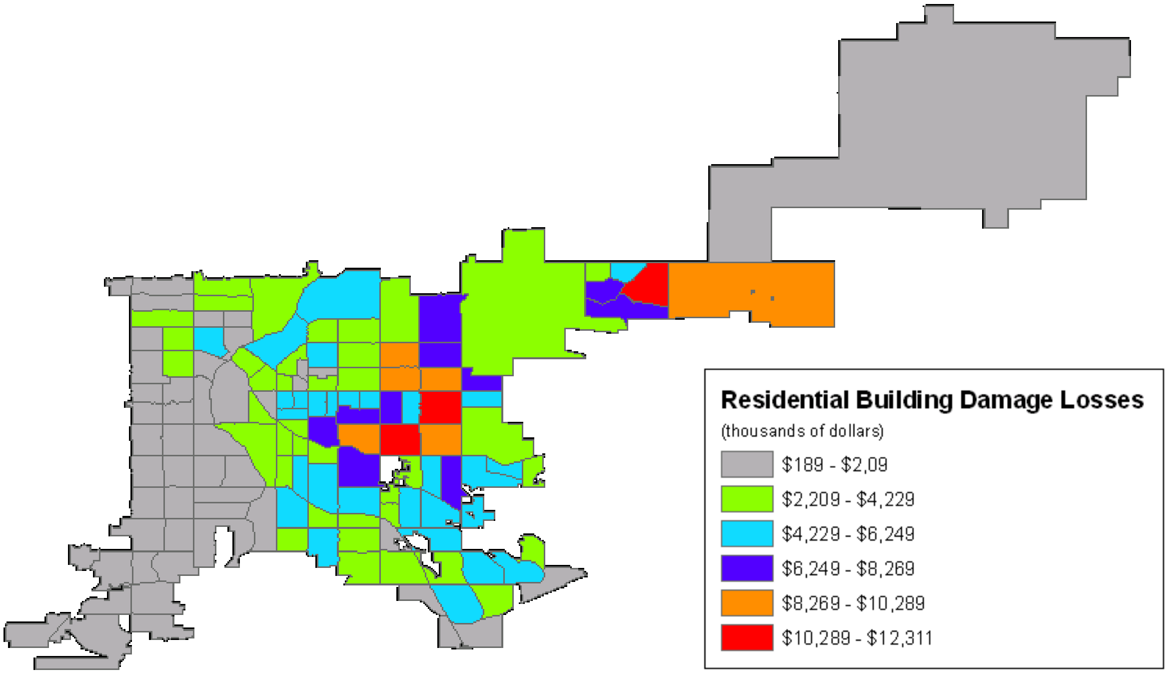


Figure7.40: Residential building damage caused by Rocky Mountain Arsenal earthquake scenario

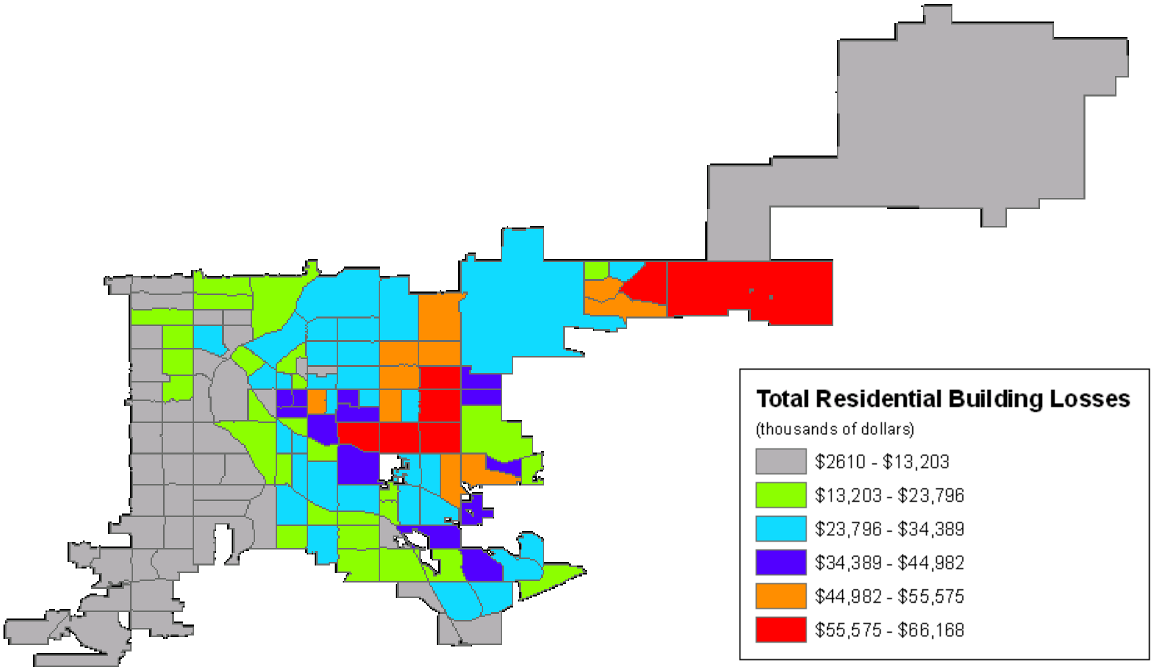


Figure 7.41: Total residential building losses caused by Rocky Mountain Arsenal earthquake scenario

The total estimated economic loss due to the earthquake is $8.98 billion in the Denver Region alone. This estimate includes both the building and lifeline related losses (based on the region's available inventory). Noting the locations where the most damage is prevalent in all of the building categories pinpoints the areas with higher levels of vulnerability that require more attention from local planners and emergency personnel. Figure 7.42 indicates the areas of higher vulnerability in terms of total building damage as a result of the Rocky Mountain Arsenal earthquake scenario.

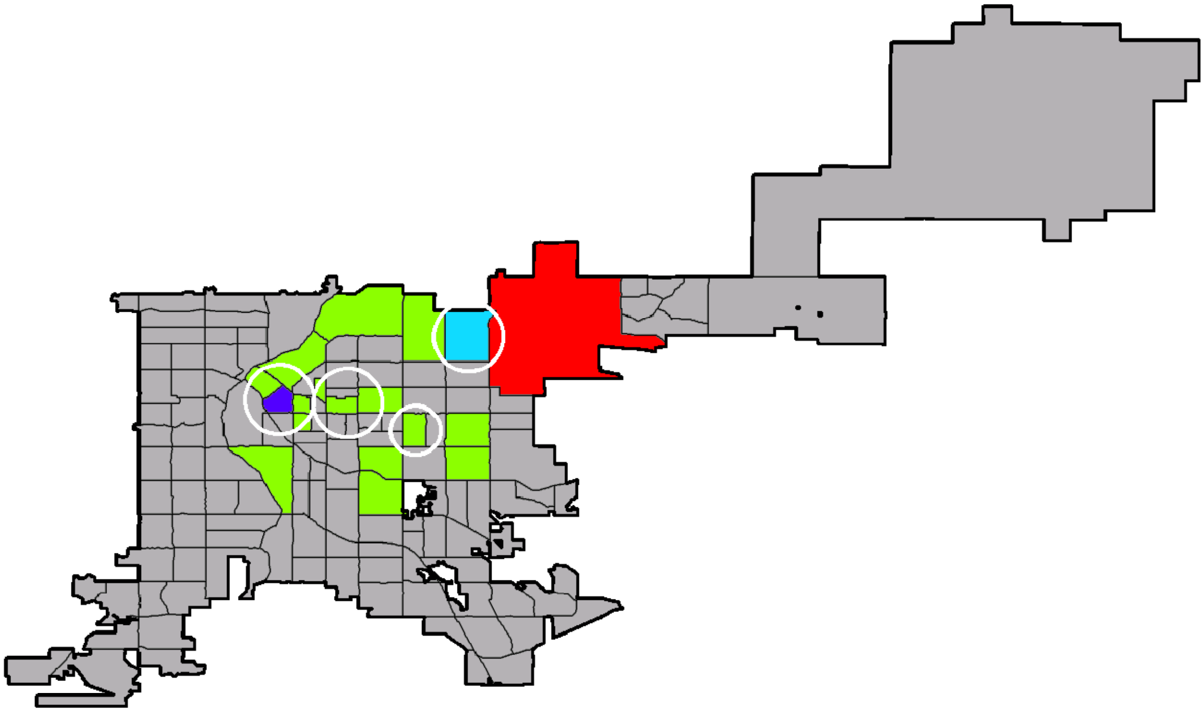


Figure 7.42: Locations of highest vulnerability in terms of total building losses (areas denoted by white circles)

The areas selected in figure 7.42 were chosen because they reflect the highest building losses per tract within a smaller area. In other words, they have the greatest monetary losses per square foot. Utility systems damage losses are equally important to observe as building damage losses. The utility systems are the power that allows each building type to function.

Utility Systems:

The six utility systems include: potable water pipelines, waste water pipelines, natural gas pipelines, oil systems, electrical power and communication. HAZUS does not have a sufficient inventory for communication facilities, and therefore that category will not be discussed further. It should be noted although that the communication systems are critical in infrastructure resiliency and are interdependent with all infrastructure systems. Therefore, local and state agencies must investigate these interdependencies to ensure that in the case of any type of stressor applied to a specific area, communications systems remain functional.

All six of these utility systems act as lifelines for an entire region. Society today has become heavily dependent on each one, thus understanding the potential damage that could occur to various stressors is important to analyze. In this earthquake scenario, both the potable water and electric power system performances were calculated. HAZUS estimated that out of a total of 239,235 households, 3,427 households would not have any potable water supply on the first day (approximately 1.4% of the total households). However, by the third day after the earthquake event, all the households would have full service. HAZUS also estimated 2,650 of the total households in the region would without electrical service (approximately 1.1% of the total households). By the third day, nearly half (1,433) would still remain without service, and after a week 482 households would still have no service. Depending on the time of year when this earthquake event occurs, lack of potable water supply and electricity can be extremely critical. A limitation of HAZUS is that it is difficult to identify the interdependencies associated with the electrical system by not specifically showing the types of buildings and facilities for which the power becomes disconnected as a result of a hazardous event. It would be useful to know which specific buildings would lose power to help determine the linkages to other parts of the infrastructure system which could be affected by the shutting down of particular facilities. For example, if the Office of Emergency Management in the City and County building (where the Multi-Agency Coordination Center provides a central place for emergency personnel to convene in the event of a disaster) is disconnected from the electrical power supply, and backup generators are not available, this could significantly affect emergency response operations. Another example is if the power supply for various traffic lights became unavailable, this could cause several accidents, and/or place the roads in a state of paralysis similar to what happened in the case studies described in chapter 2. Specific geospatial data showing all the locations of the electric distribution systems is only available to government officials and employees working for electrical companies. Therefore, only projections for the number of household without electricity are provided.

Functionality of Essential Facilities and Infrastructure Systems:

The functionality of essential facilities and critical infrastructure are additional parameters which should be considered in determining regional vulnerabilities. The essential facilities in the Denver Region examined in this study include: hospitals, police stations, emergency operation facilities, a fire station, natural gas facilities, oil facilities, and schools. HAZUS provides resulting probabilities of functionality after the event of a defined hazard scenario. The probability of functionality "is defined as the probability, given an initial level of damage after the earthquake, of the component operating at a certain capacity after a specified period of time" (HAZUS 2010). For example, if a bridge type is 14% functional after one day and 60% functional after three months, this can be interpreted as, "that after one day, 14% of the bridges of this type would be functional and after three months, 60% of these bridges would be functional" (HAZUS 2010). In the case of bridges, functionality is defined as the ability to carry the same type and amount of traffic load as prior to the event.

A few of the regional infrastructure systems experiencing no loss in functionality include: highway segments, railway segments, the airport (Denver International Airport), and all the airport's runways. However, there are several critical facilities and critical infrastructure which would experience a significant loss in functionality. HAZUS results indicated hospitals as having the greatest decrease in functionality immediately after the earthquake event. Figure 7.43 below, shows each of the hospital's probability of functionality three days after the earthquake still below 50%. Prior to the earthquake, the region's inventory for hospital beds available for use was 3,328. On the same day as the earthquake, only 630 of these hospital beds were available for both the current patients as well as new patients injured by the earthquake. After only one week, fewer than 50% of the beds would be available. The inability to accommodate those injured by the earthquake translates into a higher casualty rate.

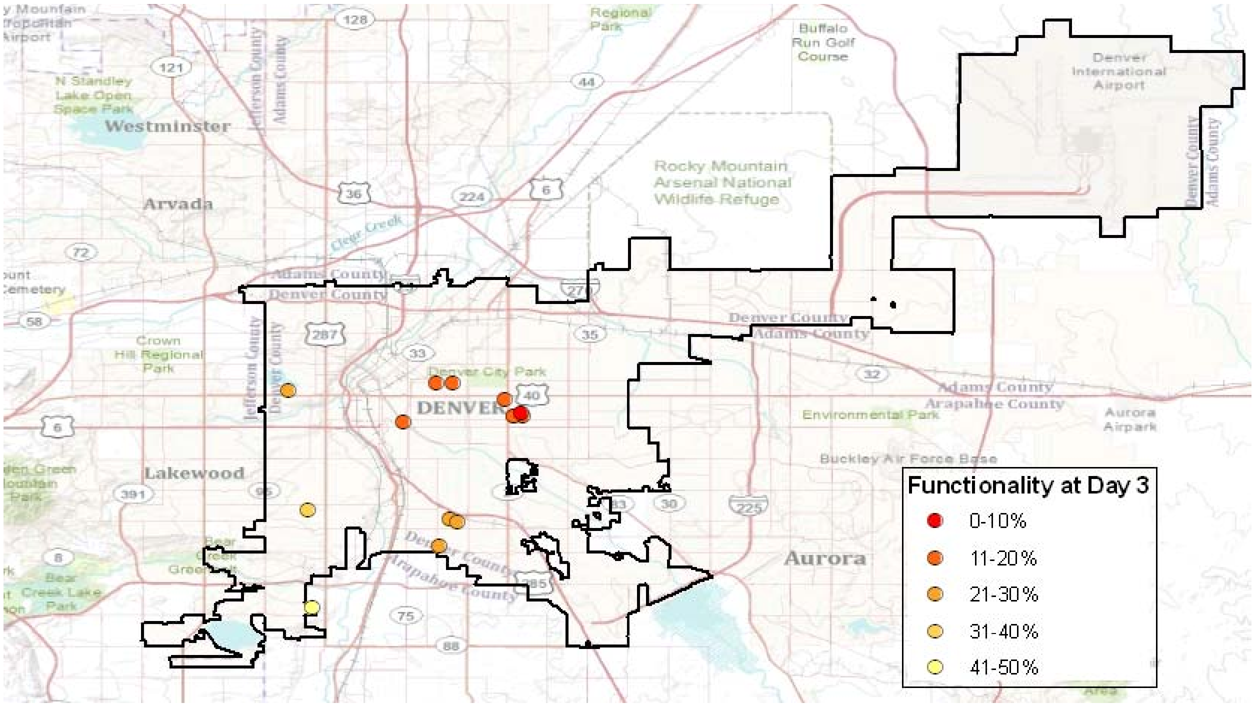


Figure 7.43: Regional hospital functionality three days after the earthquake

All of the schools within the region were affected, with most schools at a probability of functionality less than 60% on the day of the earthquake event. Figure 7.44 shows the functionality of all 217 schools within the region.

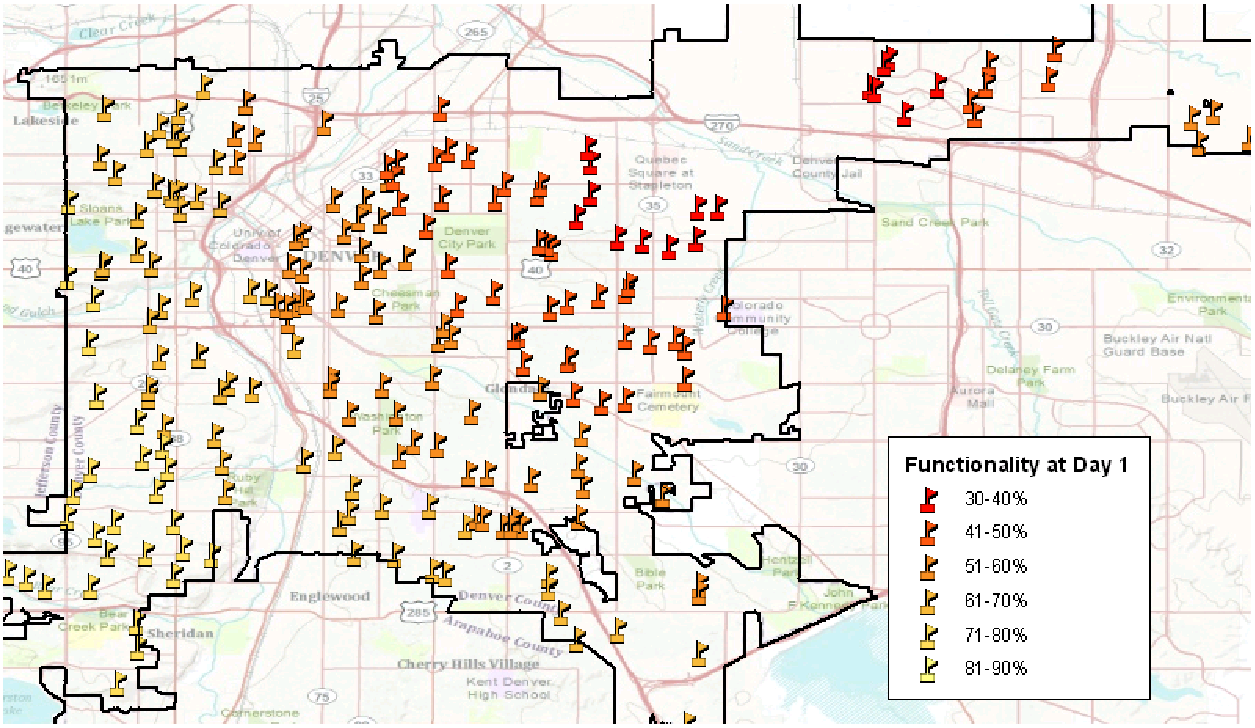


Figure 7.44: School functionality one day after the earthquake event

Police stations are another critical facility needed in the event of an emergency. Figure 7.45 shows the functionality of all the police stations included in the HAZUS's built-in inventory, three days after the earthquake. The probability of functionality for each of the police stations in the region is below 75%, and four are below 45%.

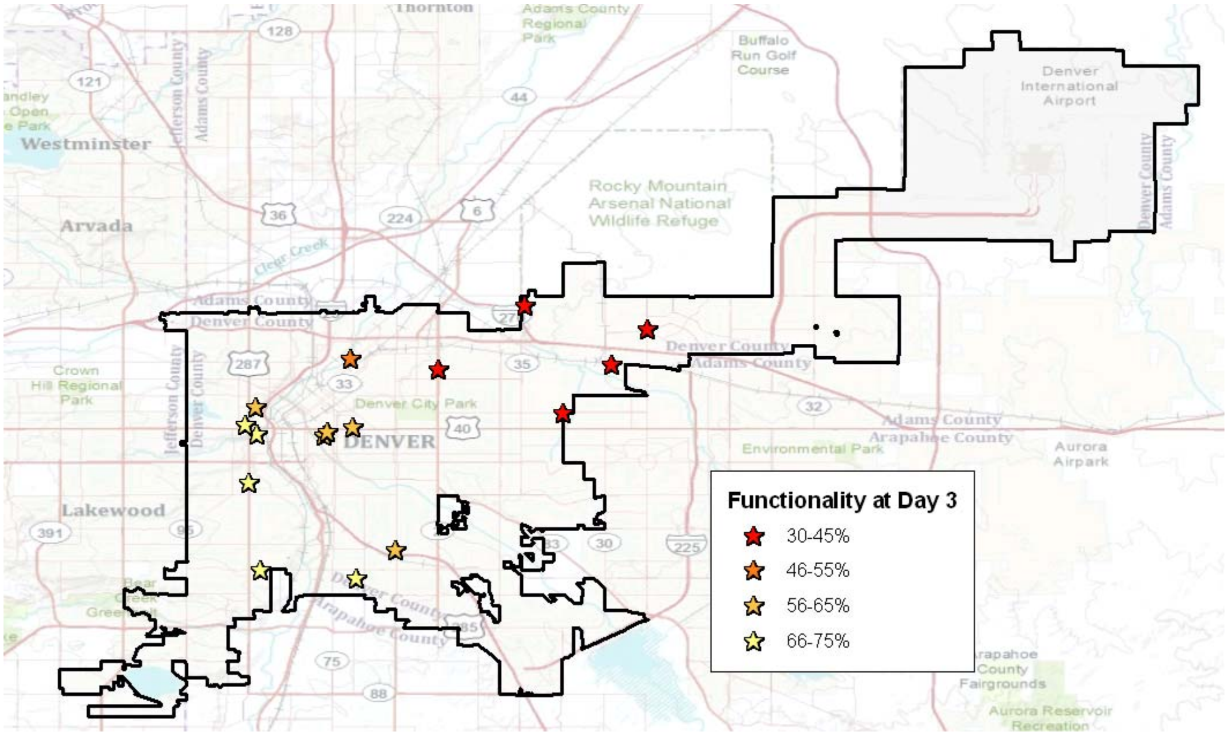


Figure 7.45: Police station functionality three days after the earthquake event

The essential facility inventory in HAZUS includes one fire station, the Denver Fire Department located in downtown Denver (figure 7.46). This fire station has a probability of functionality at day three of 59.3%. The location of this fire station, being downtown near several other essential facilities including hospitals and police stations, makes this facility highly important. As discussed previously, earthquakes are typically joined by fire damage. If the fire station is no longer functioning, the response to fires in the area will be severely reduced, allowing for more damage to occur.

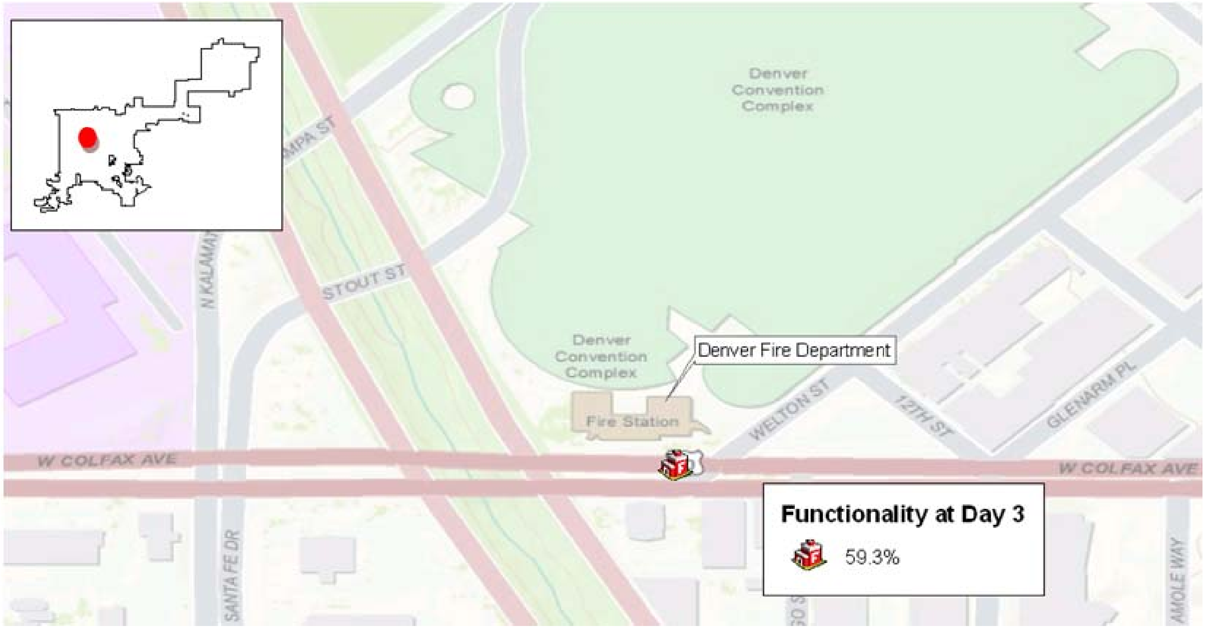


Figure 7.46: Fire station functionality three days after the earthquake event

There are two emergency operation centers in the Denver Region: the Denver Public Safety Review and the Office of Emergency Management (seen in figure 7.47). Both of these facilities have a probability of functionality slightly under 60%. The Office of Emergency Management holds the Multi-Agency Coordination Center (MACC) providing state, federal, and local agencies a central place to convene in the event of an emergency (DOLA 2010). By having a representative from all the operations sections (including law enforcement, fire services, public works, mass care, communications, medical, public health, environmental health, airport, and private sector), issues resulting from the infrastructure's interdependencies can be resolved quickly and more efficiently (Alexander 2010). Therefore if this facility is not usable due to either structural damage, electrical outage, or another scenario, operations will be difficult to perform. All emergency management offices are required to have an alternative location in the case of an emergency, therefore through a study conducted similar to this scenario, an appropriate alternative location can be assigned by observing which areas within the Denver Region experience the least physical damage

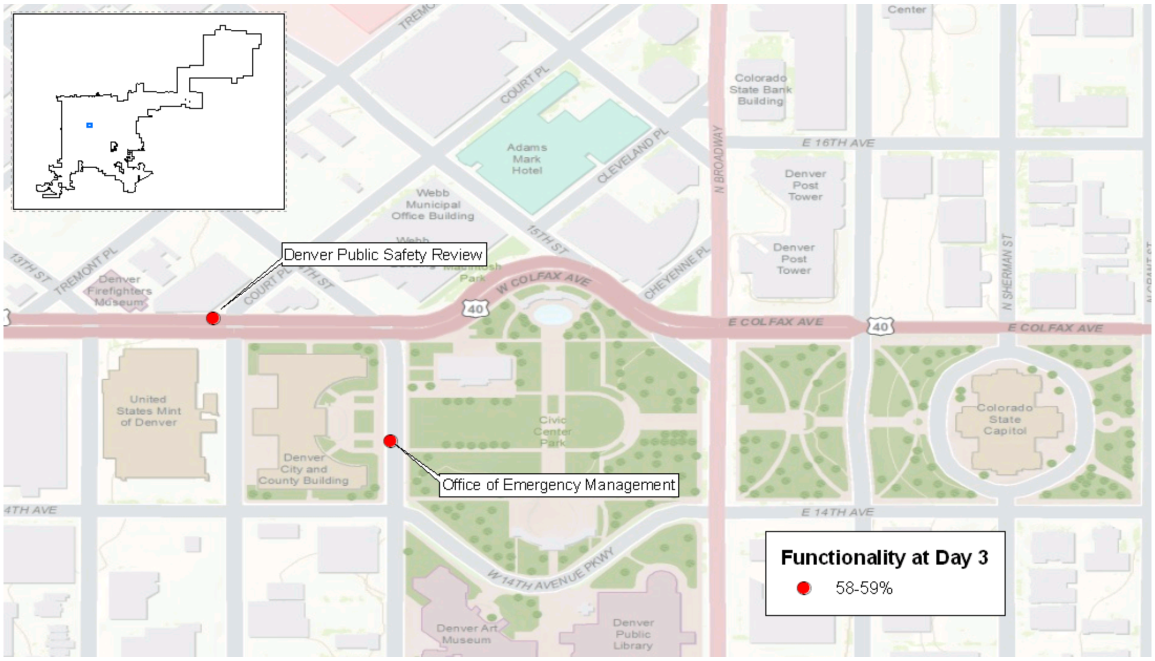


Figure 7.47: Emergency operation centers' functionality three days after the earthquake event

The functionality of essential facilities is important to recognize, but the functionality of these facilities are meaningless if the transportation and utility systems supporting these facilities are non-functional. For example, if a highway bridge has collapsed, the entire highway segment would be out of commission, preventing ambulances or other emergency vehicles from reaching their destinations including hospitals and areas where emergency personnel are needed. Figure 7.48 below, presents the functionality of highway bridges on the day of the event. Several bridges along major highway corridors are affected, placing a handicap on the transportation system.

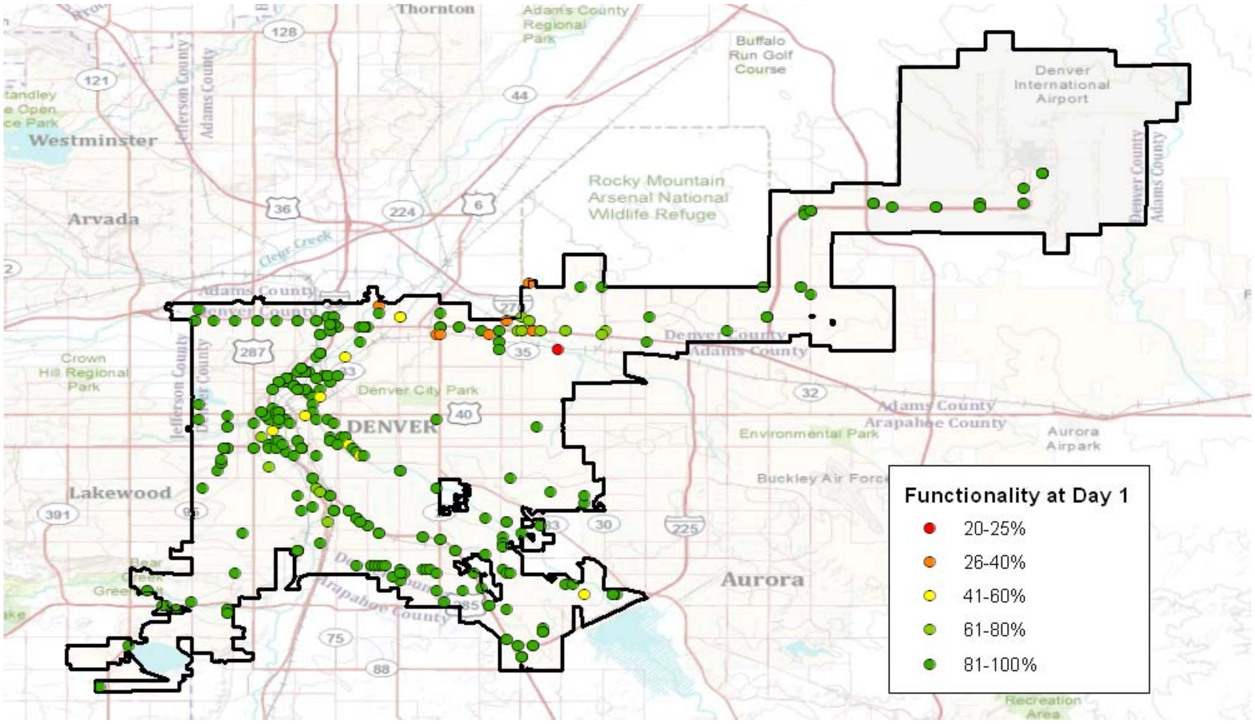


Figure 7.48: Regional highway bridge functionalities one day after earthquake event

Railway bridges did not experience as much damage as the highway bridges. Railway bridges are important in the transportation of materials in and out of the Denver Region. The failure of a railway bridge would cease operation on any rail lines involved, affecting both the Denver Region and surrounding regions dependent on the same rail line. The railway bridge probabilities of functionality on the first day after the earthquake are seen in figure 7.49, and the probabilities of the railway facilities' functionality are shown in figure 7.50.

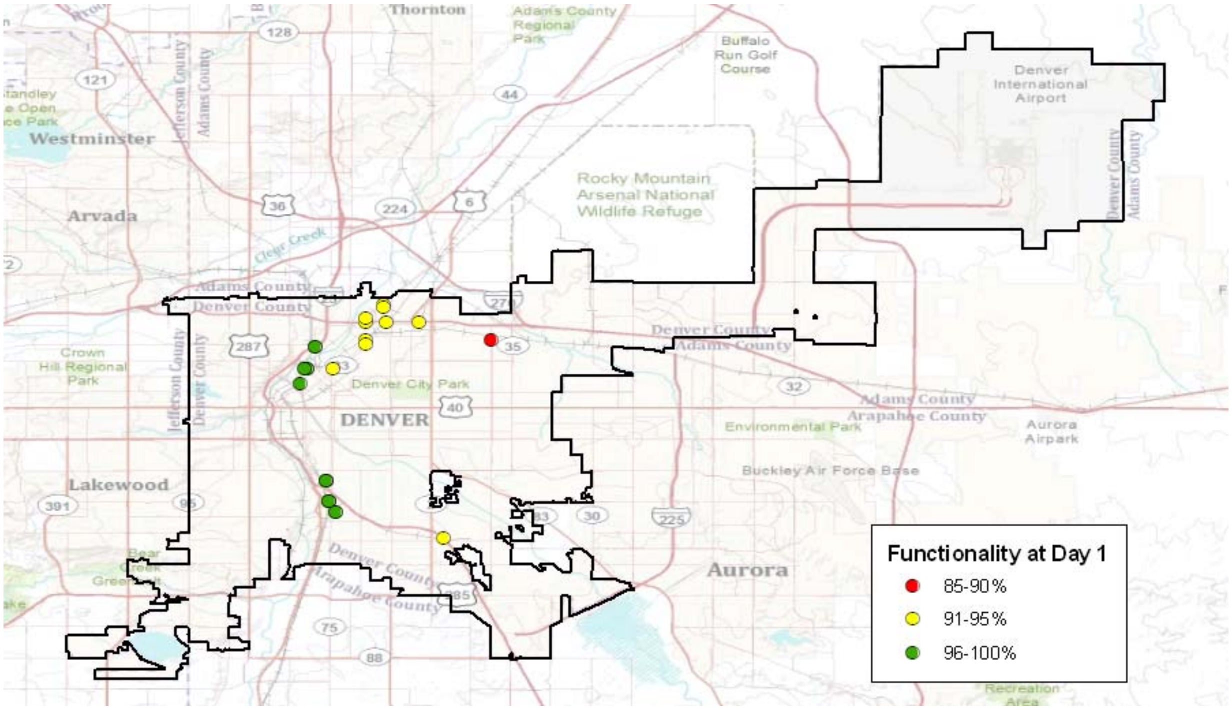


Figure 7.49: Railway bridge functionality on the day of the earthquake event

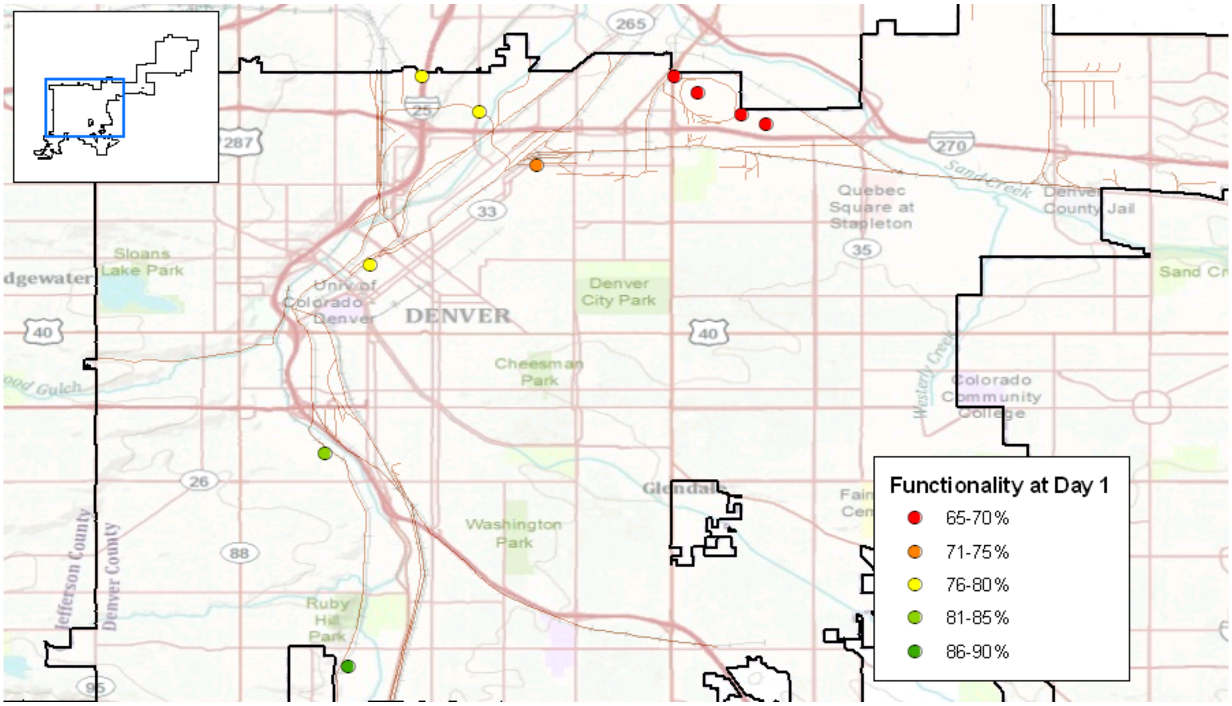


Figure 7.50: Railway facility functionality on the day of the earthquake event

Denver’s light rail system is an efficient method of transportation connecting downtown and south Denver. Future plans for the Denver transportation system include expanding the light rail system to traverse most of the region. Based on the results from HAZUS, the light rail segments maintained full probability of functionality, and all the light rail facilities along the various routes met a probability of functionality above 75% immediately after the earthquake event took place (seen in figure 7.51).

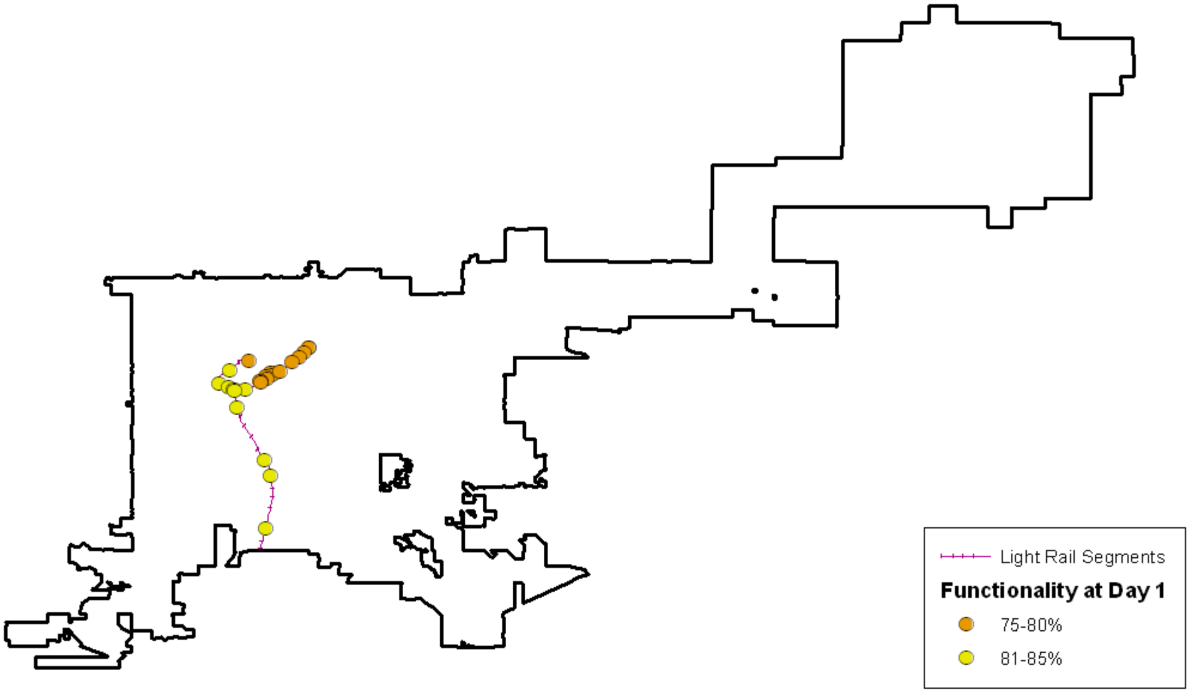


Figure 7.51: Light rail facilities functionality one day after earthquake event

All the bus facilities had a similar performance as the light rail facilities with functionality on the day of the event above 70% (seen in figure 7.52).

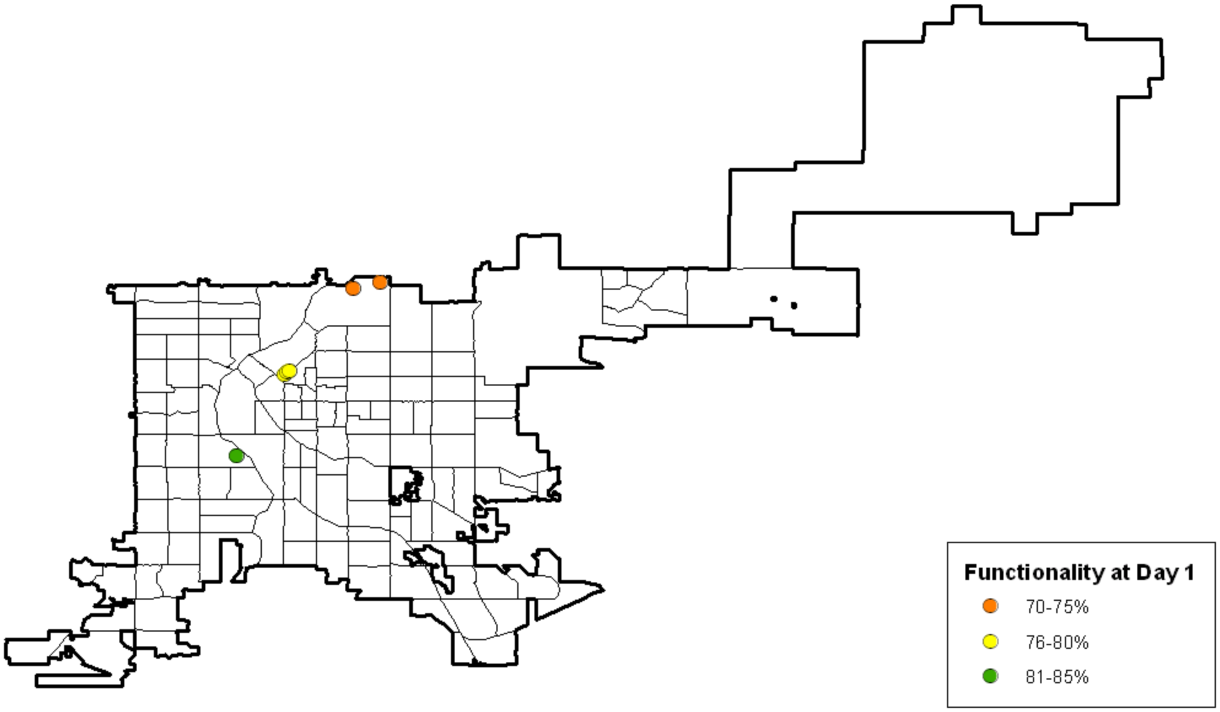


Figure 7.52: Bus facility functionality one day after earthquake event

The functionality of each different component of the entire transportation system is important foremost for the ability for emergency response operations to be unaffected. Second, the functionality of each transportation system component has an affect on the ability for the population to continue business operations. The functionality of the different transportation systems must be looked at in conjunction with the preferred method of transportation by the population. For instance, if the functionality of the light rail system is at 50% and the functionality of a highway bridge is 70%, the effect from the light rail system having less functionality does not necessarily translate to greater effect on business operations. Instead the inoperability of a highway bridge could result in a more drastic effect on the region's business operations since a majority of the populations uses their own individual vehicle as their main method of transportation, versus public transportation. The following figures (figures 7.53 through 7.56) identify the percentage of the population per census tract using a specific mode of transportation.

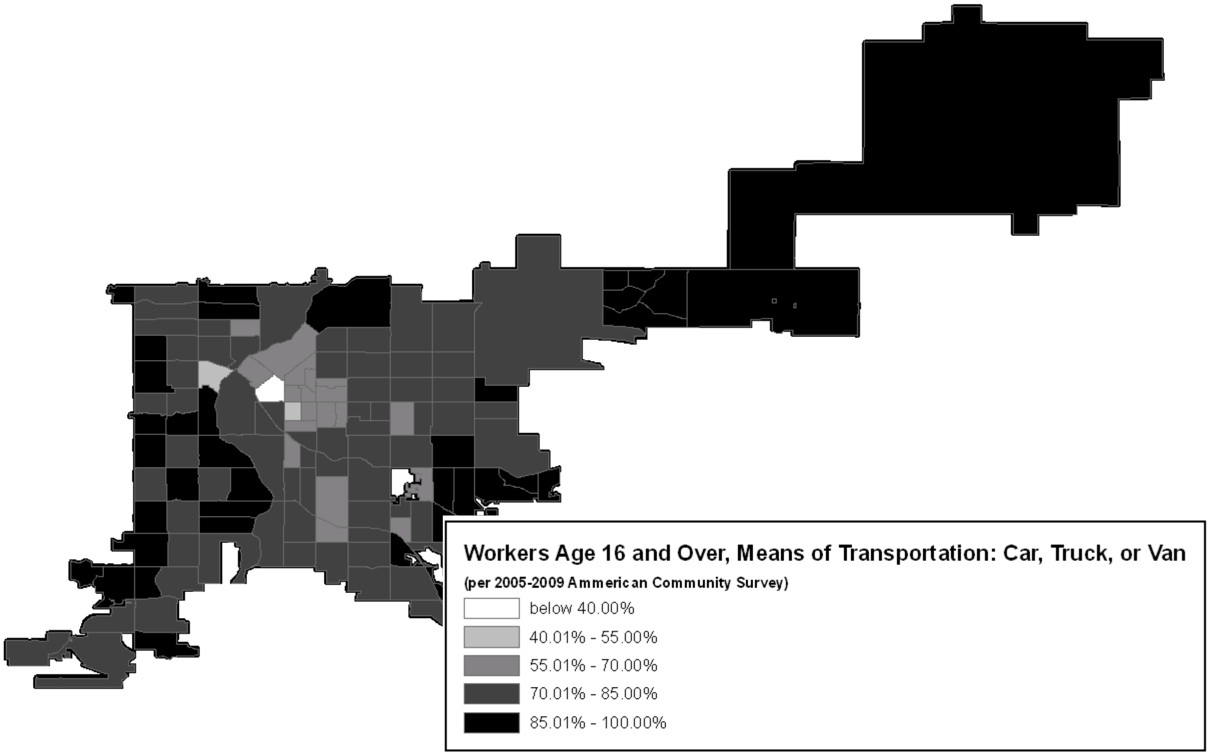


Figure 7.53: Workers Age 16 and over whose means of transportation is by car, truck, or van

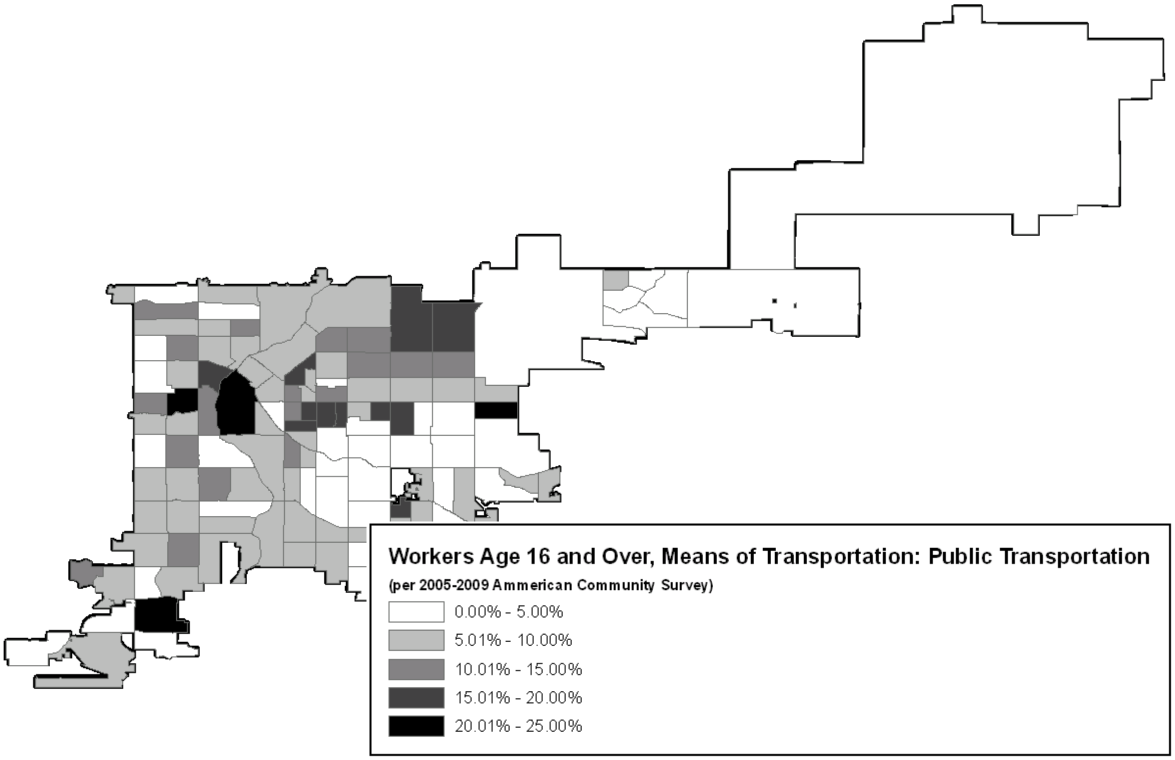


Figure 7.54: Workers Age 16 and over whose means of transportation is by public transportation

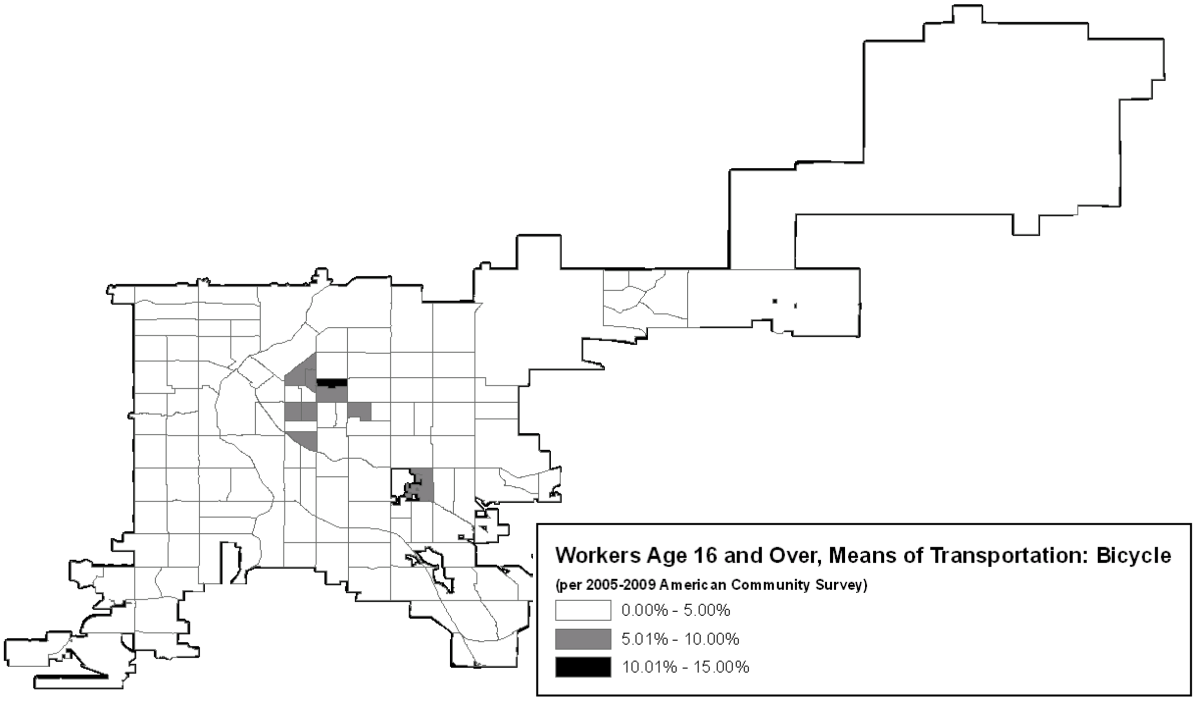


Figure 7.55: Workers Age 16 and over whose means of transportation is by bicycle

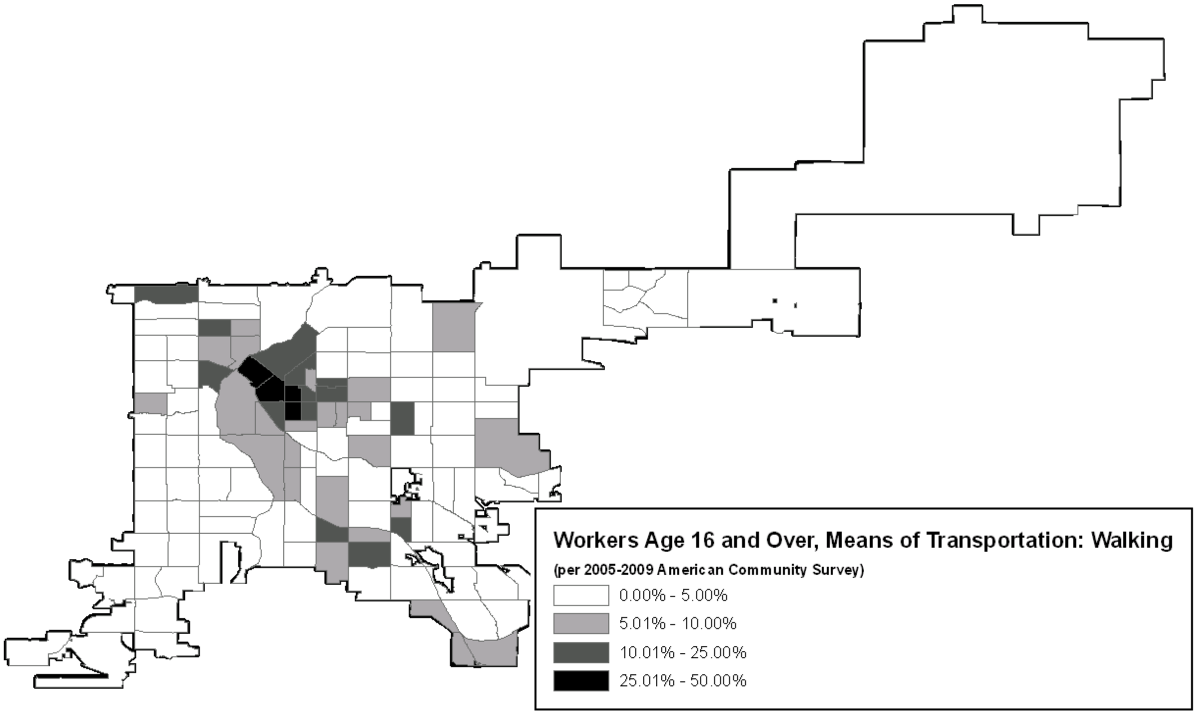
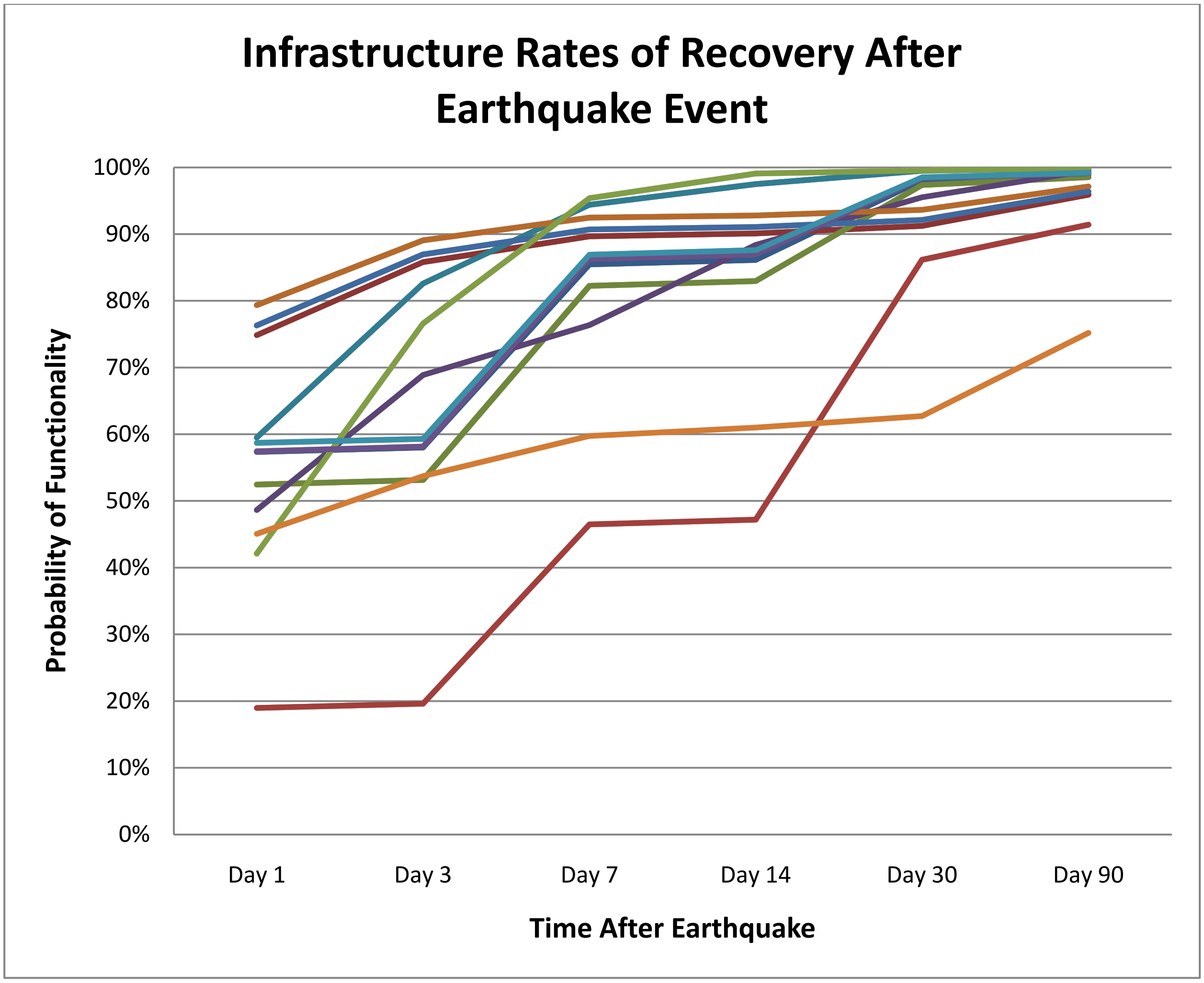


Figure 7.56: Workers Age 16 and over whose means of transportation is by walking

Rate of recovery for each infrastructure system and essential facility is another key aspect that is important for resiliency. Using the probabilities of functionality from the HAZUS output, given at specific time intervals after the date of the scenario event, the rate of recovery was investigated. The vulnerability of an area is not only observed directly after a stressor is applied, but also observed during the recovery period. The longer the recovery period, the more vulnerable the area is as a result of the loss of functionality. Figure7.57 below displays the rate of recovery for all of the facilities with a probability of functionality below 90% on the day of the earthquake event (the number in parenthesis next to the facility type indicates the number of facilities included in the rate of recovery sample). Those not included because they have a probability of functionality of greater than 90% on the first day are the airport, the airport runways, the railway segments, the railway bridges, the natural gas facility, the light rail facilities, the light rail bridge, and the highway segments.



	Day 1	Day 3	Day 7	Day 14	Day 30	Day 90
— School Facilities (217)	57.35%	58.01%	85.45%	86.12%	98.09%	98.95%
— Railway Facilities (10)	74.85%	85.81%	89.66%	90.09%	91.23%	95.91%
— Police Station Facilities (17)	52.46%	53.15%	82.24%	82.96%	97.35%	98.54%
— Oil Facilities (7)	48.64%	68.89%	76.36%	88.37%	95.51%	99.53%
— Natural Gas Facilities (1)	59.50%	82.60%	94.40%	97.50%	99.50%	99.90%
— Light Rail Facilities (26)	79.35%	89.07%	92.46%	92.78%	93.63%	97.13%
— Bus Facilities (6)	76.30%	86.95%	90.70%	91.07%	92.12%	96.37%
— Hospital Facilities (14)	18.96%	19.61%	46.48%	47.19%	86.15%	91.41%
— Electrical Power Facilities (4)	42.10%	76.60%	95.38%	99.08%	99.55%	99.90%
— Emergency Operation Facilities (2)	57.45%	58.15%	86.25%	86.95%	98.40%	99.10%
— Fire Station Facility (1)	58.70%	59.30%	86.90%	87.60%	98.50%	99.20%
— Highway Bridges (22)	45.05%	53.72%	59.74%	61.00%	62.73%	75.20%

Figure 7.57: Critical infrastructure rate of recovery for Rocky Mountain Arsenal Earthquake scenario

The recovery rates provided above indicate hospital facilities and highway bridges as having the longest recovery rate, reaching only 47% and 61% functionality, respectively, after 14 days. Following are oil facilities and police stations. These recovery rates express several weaknesses in the time it takes to restore the infrastructure system to its original state. These issues should be addressed in Denver's mitigation plan.

Furthermore, another portion of identifying regional vulnerabilities relates to the social characteristics. Understanding the characteristics and the behaviors of the population within a defined region leads to an understanding of how this population will be affected and will adapt to a stressor applied to the various infrastructure systems. The individual means of transportation is one of these characteristics. Additional characteristics include educational attainment, household income, age, race, and other identifiers. These characteristics can be used to pinpoint the location of vulnerable populations, and aid in developing mitigation plans. Figures 7.58 through 7.67 visually identify these characteristics for the Denver Region.

Educational Attainment:

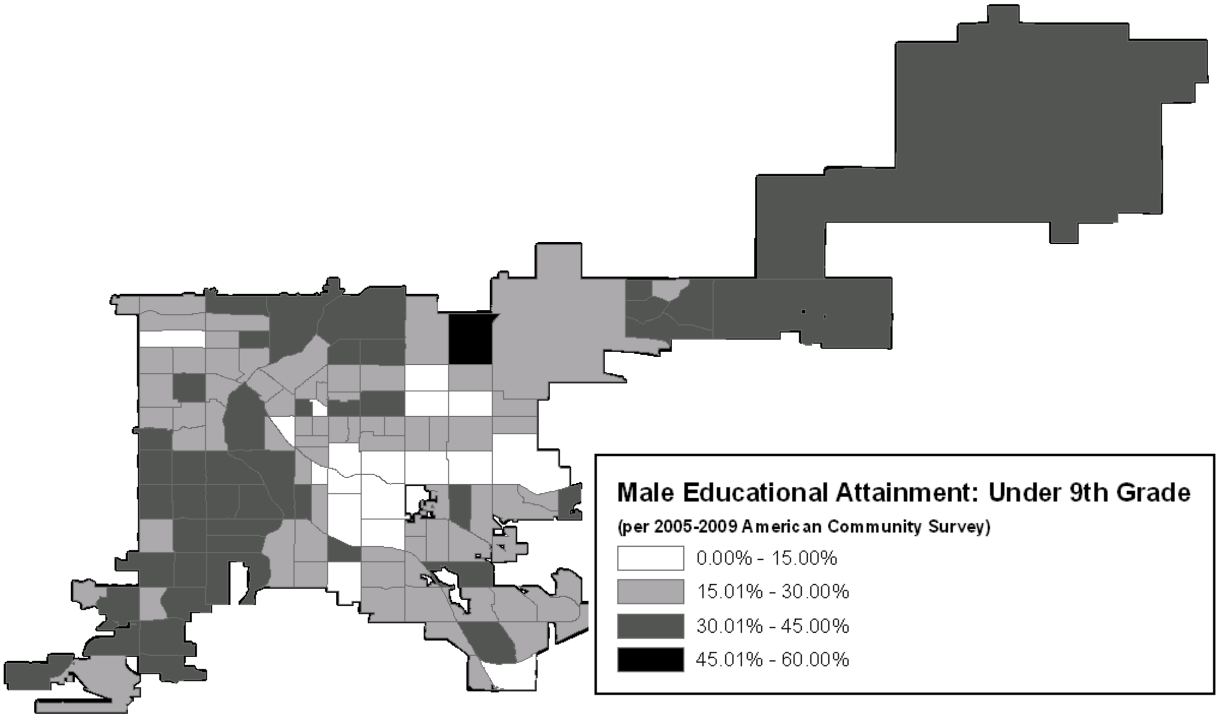


Figure 7.58: Educational attainment under 9th grade for males age 25 and over

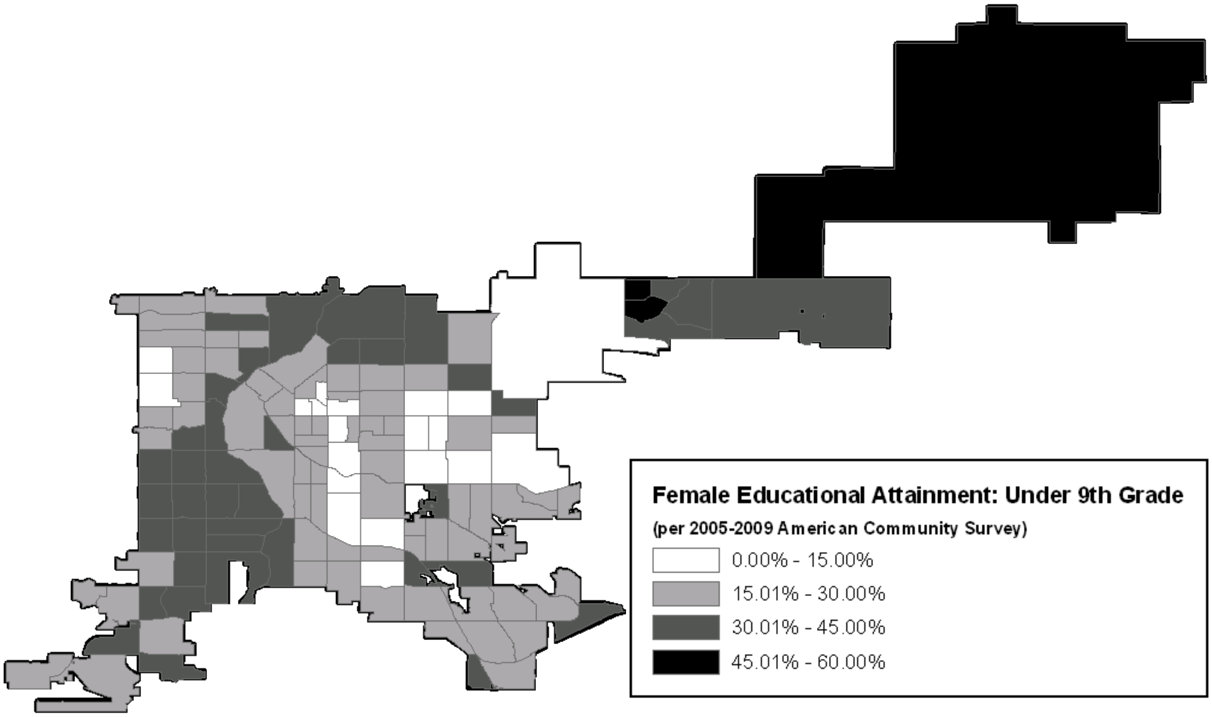


Figure 7.59: Educational attainment under 9th grade for females age 25 and over

Household Income:

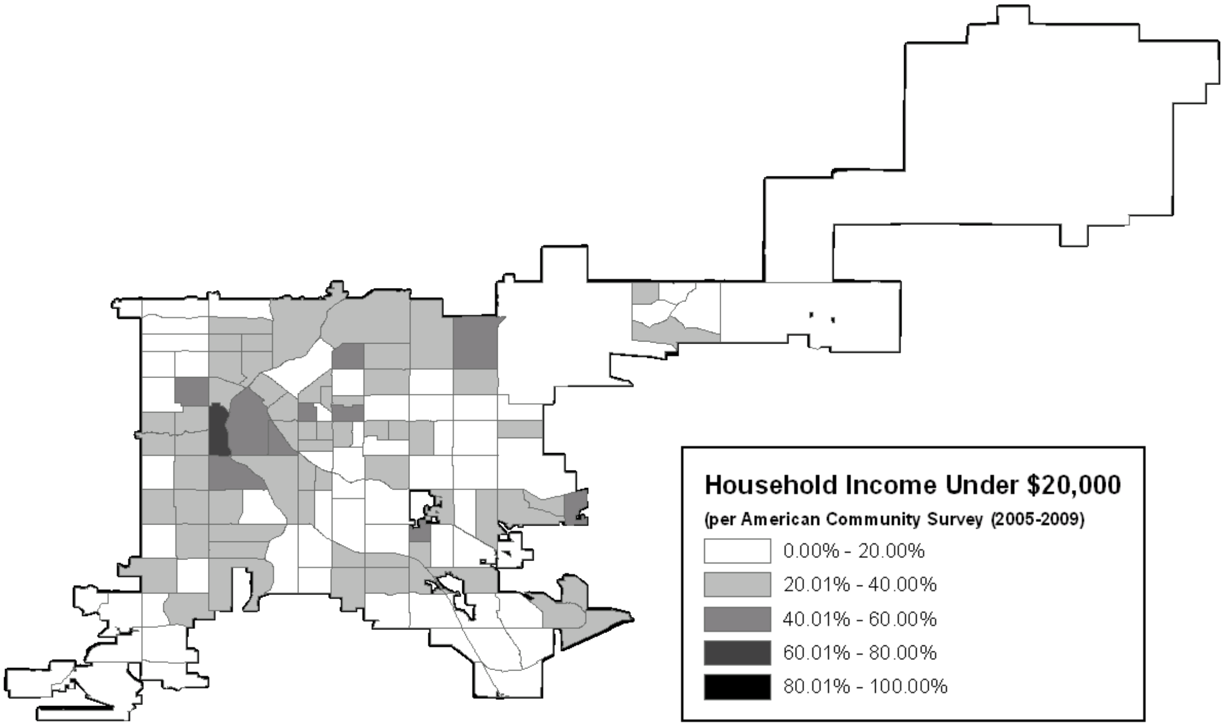


Figure 7.60: Percentage of households with an income under $20,000 per census tract

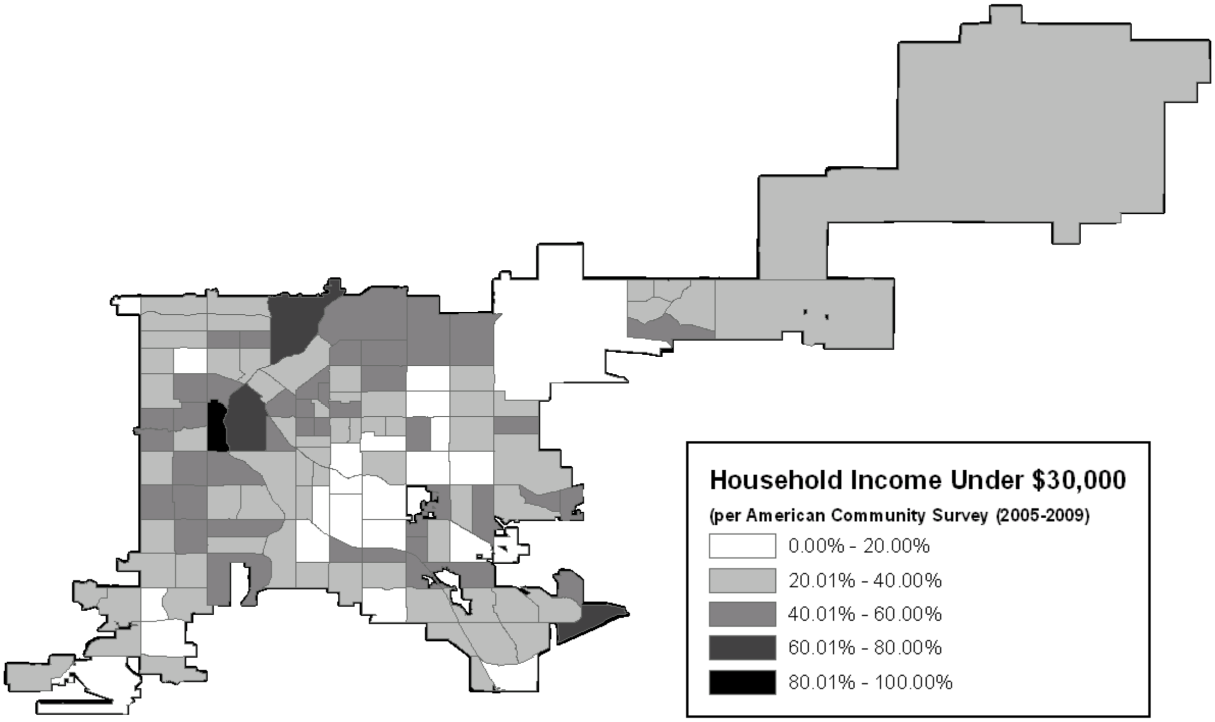


Figure 7.61: Percentage of households with an income under $30,000 per census tract

Age:

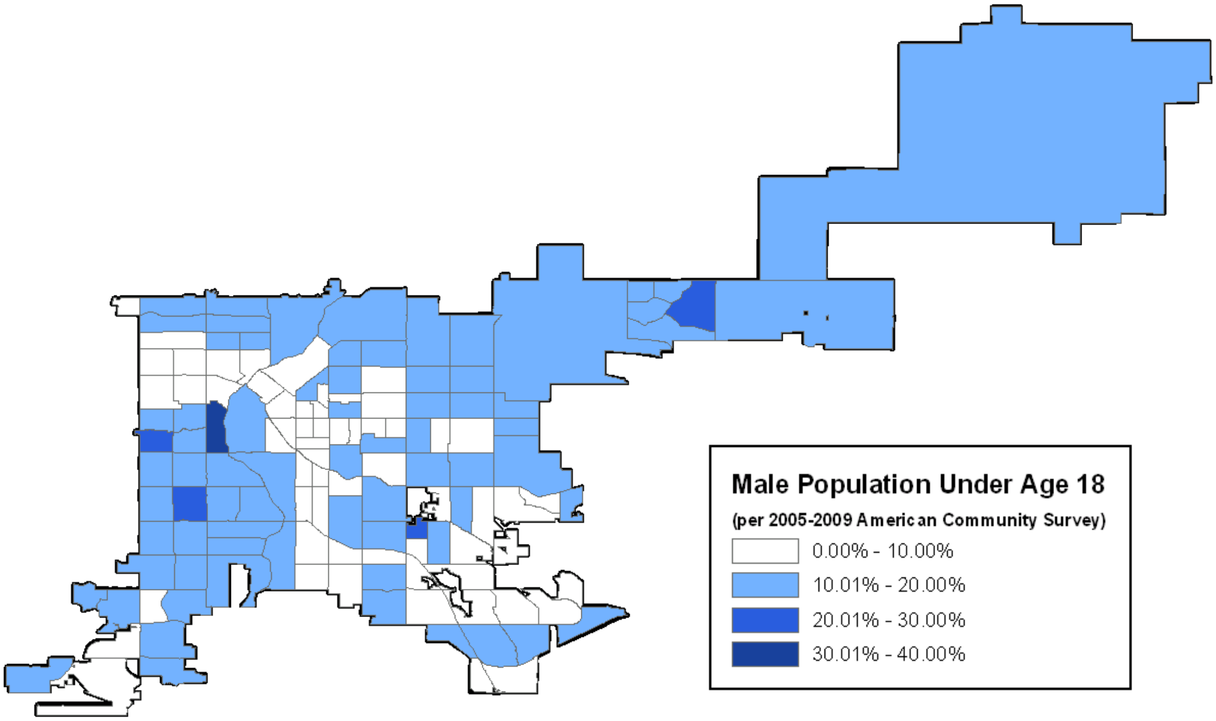


Figure 7.62: Percentage of male population under age 18 per census tract

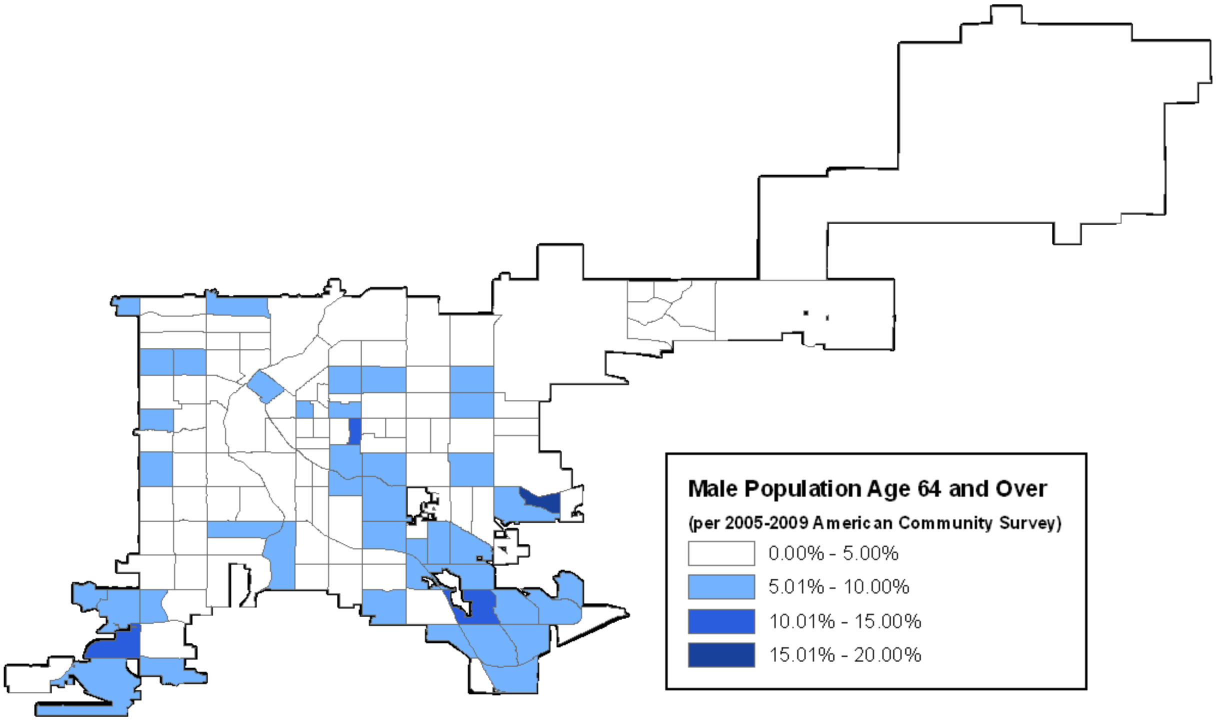


Figure 7.63: Percentage of male population age 64 and over per census tract

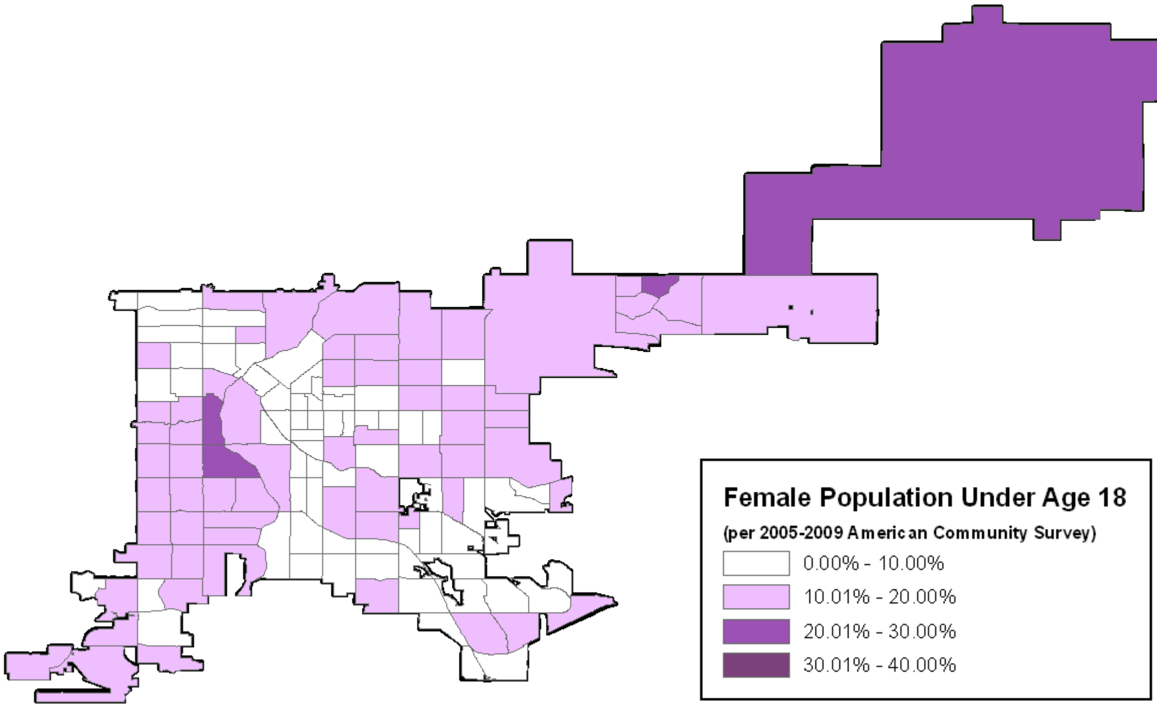


Figure 7.64: Percentage of female population under age 18 per census tract

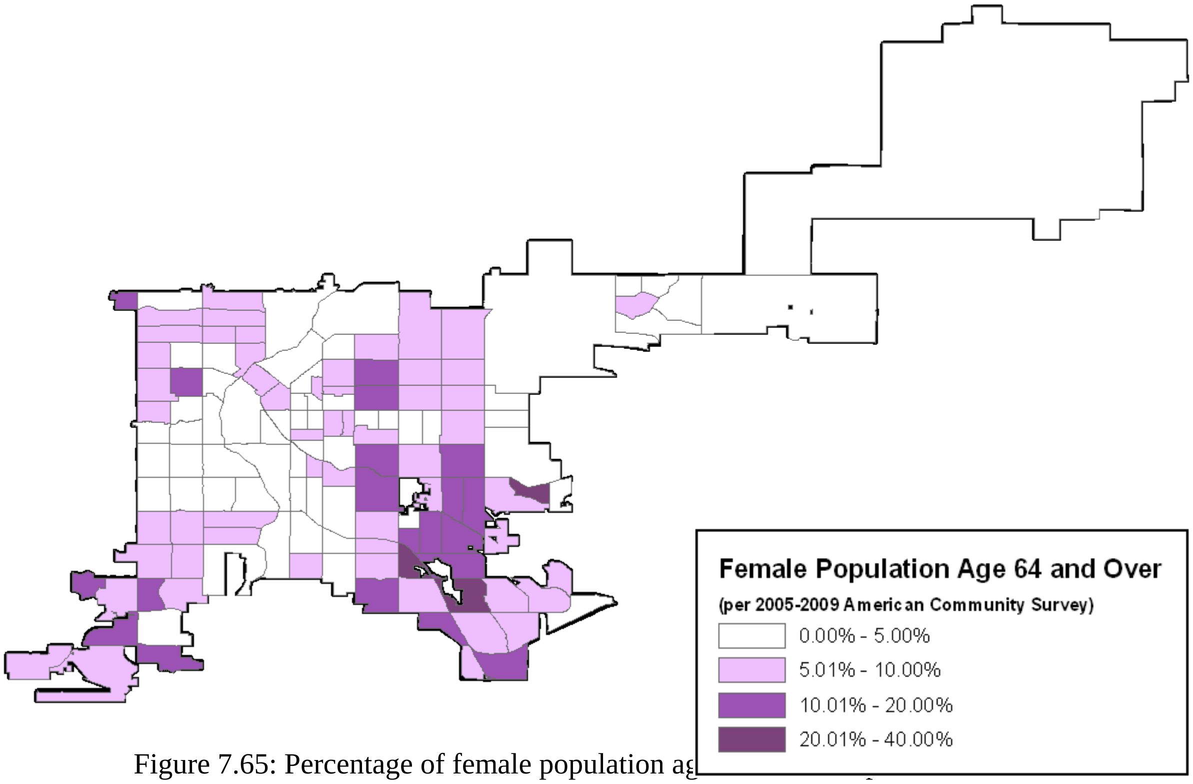


Figure 7.65: Percentage of female population ag

Race:

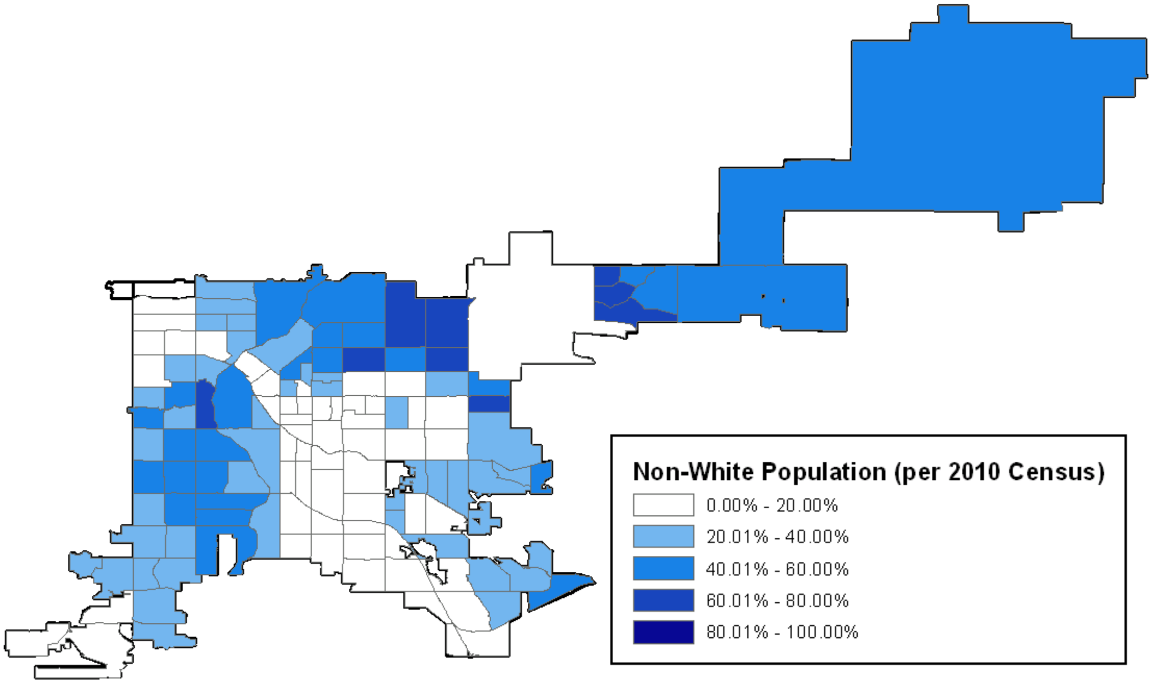


Figure 7.66: Percentage of population that is non-White per census tract

Figure 7.67 below shows the percentage of the population that is Hispanic or Latino per census tract. The Hispanic population consists of 31.8% of the total population per the 2010 Census data. The Hispanic and Latino population was chosen for Figure 7.67 since it is the second highest percentage representing a single race within the total population of the Denver Region.

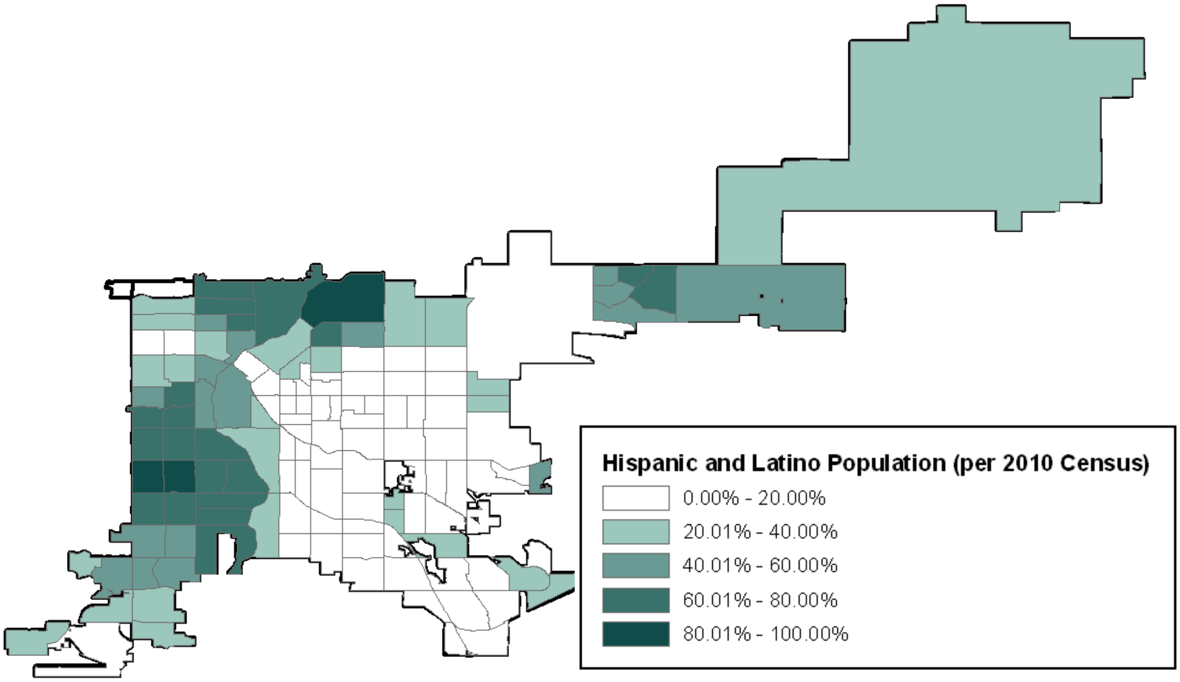


Figure 7.67: Percentage of population that is Hispanic or Latino per census tract

All of the social characteristics shown in the figures above clearly identify particular patterned locations of where social vulnerability is present. Figure 7.68 below, displays these specific areas of exceptional vulnerability levels (denoted by circles):

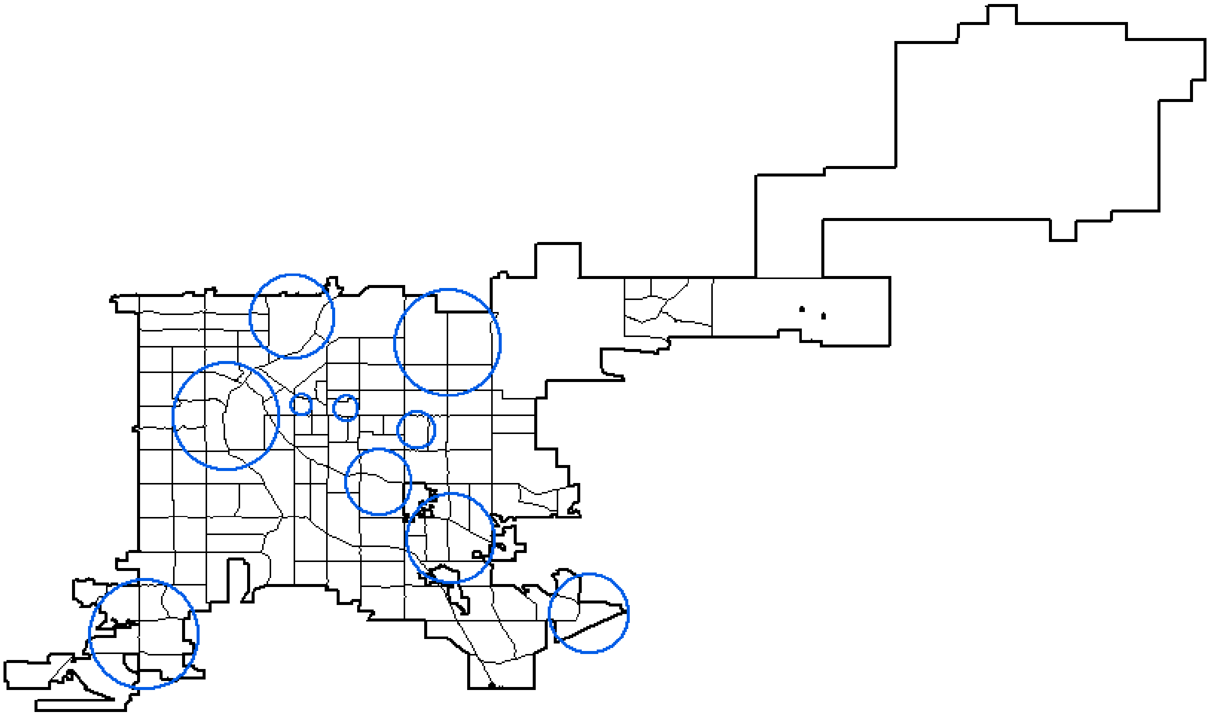


Figure 7.68: Locations of where social vulnerability exists in the Denver Region

The same identified areas indicating where there are higher levels of social vulnerability are overlaid on figures from previous parts of this section showing the casualties and the total building losses for all the building type categories for the Rocky Mountain Arsenal earthquake. The results are shown in figures 7.69 and 7.70 below.

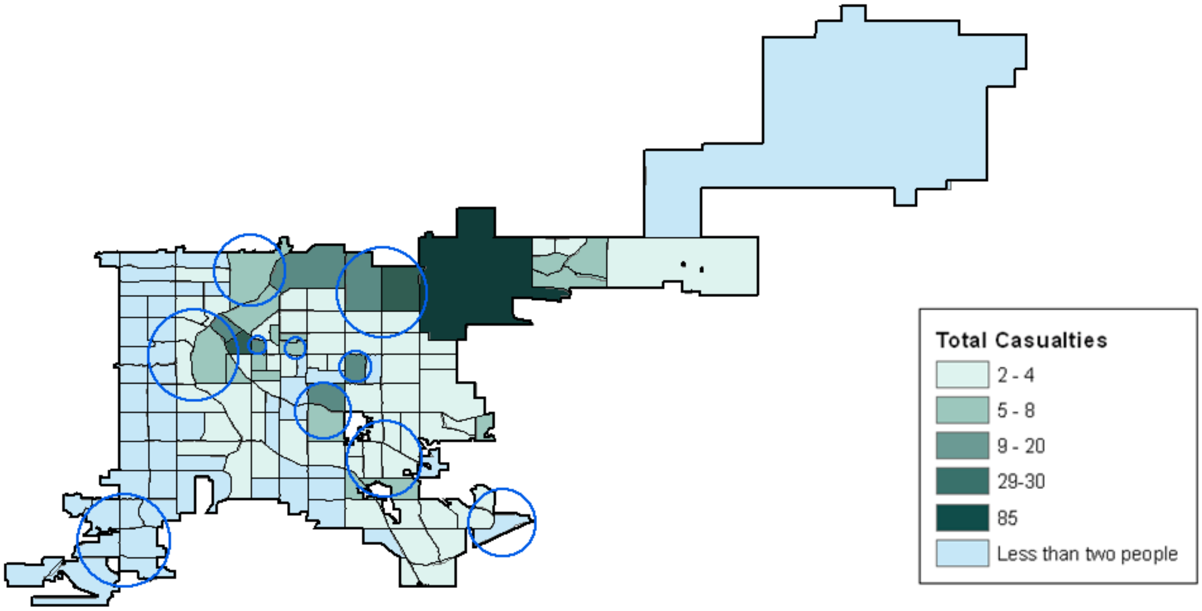


Figure 7.69: Combined map showing areas of social vulnerability (blue circles) and total casualties (due to Rocky Mountain Fault earthquake scenario)

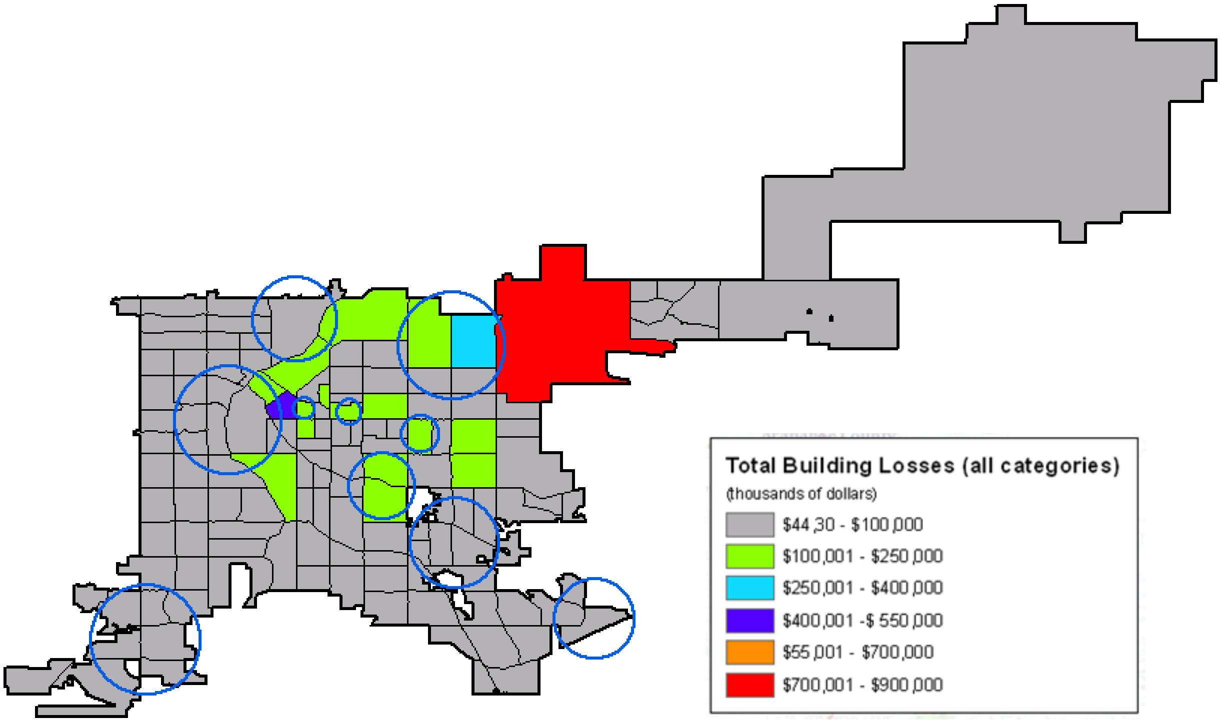
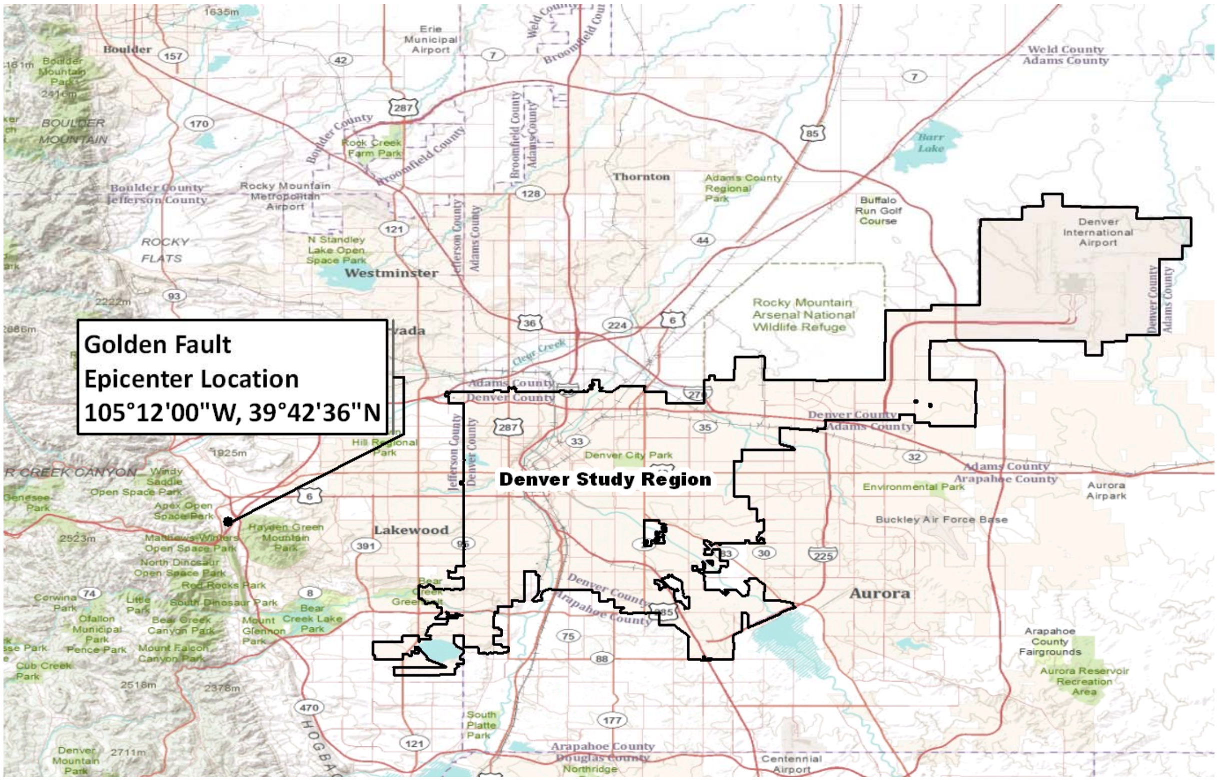


Figure 7.70: Combined map showing areas of social vulnerability (blue circles) and total building losses (due to Rocky Mountain Fault earthquake scenario)

Using figures showing the correlations between economic losses, social vulnerabilities, and physical interdependencies within a region can provide a valuable tool for development and mitigation planning. This methodology of assessing risk may also prove useful in emergency response planning.

7.2.3 Golden Fault Earthquake:

A similar case study to the Rocky Mountain Arsenal Earthquake was conducted simulating an earthquake along the Golden Fault Line. The intention is to be able to compare a couple of different earthquake scenarios occurring on two different faults located on different sides of Denver, and then examine the results to find similarities. If the locations showing the most physical and economic loss are the same, then these are areas that should be further examined to mitigate potential loss in the future.



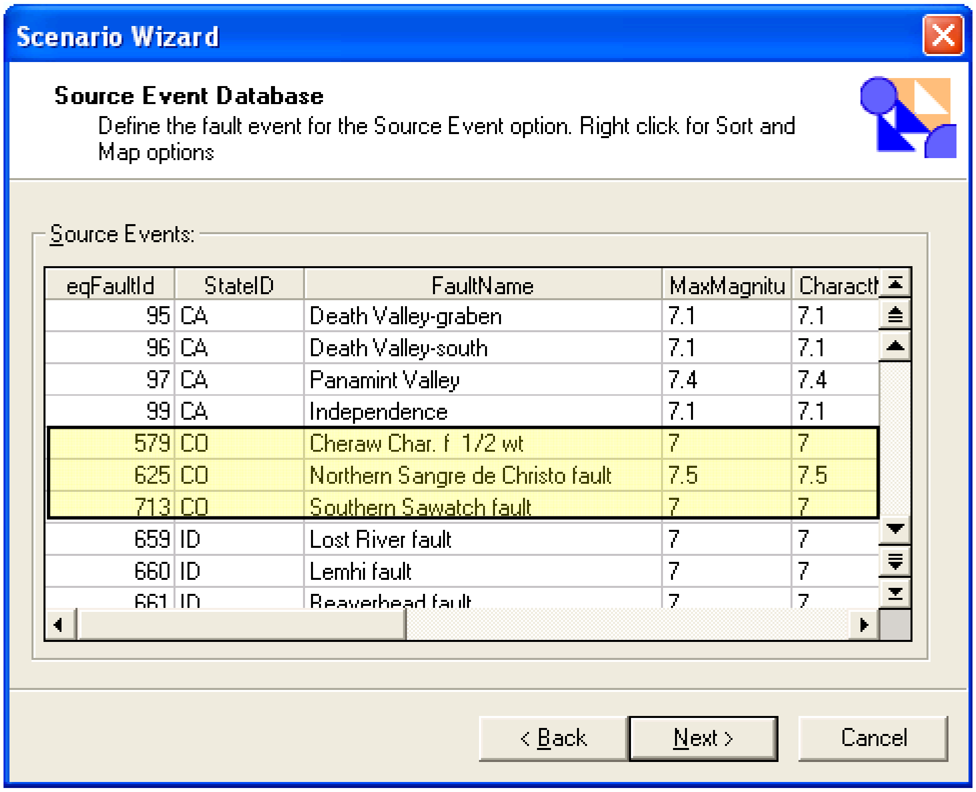
Golden Fault
Epicenter Location
105°12'00"W, 39°42'36"N

Denver Study Region

Figure 7.71: Epicenter location of Golden Fault Line earthquake scenario

Faults identified to have moved between 130,000 and 2 million years ago are considered potentially active faults, and those with movements within the last 130,000 years are considered active faults. This 2 million year time frame is called the Quaternary Period. The quaternary-age geologic deposits have been studied to examine fault activity. For instance, "if a fault offsets or deforms a deposit, the most recent movement of the fault happened since that deposit formed. If a deposit covers a fault and is not offset or deformed by it, then the last movement of the fault predates the deposit" (CEHMC 2008). Evidence from these deposits has shown that earthquakes with a magnitude 7.0 or higher have probably occurred on many faults in Colorado since humans have lived here (Matthews 2003). The Golden fault is part of the quaternary period, with the potential of an earthquake with a "Maximum Credible Magnitude" of 6.5, as previously stated. The Golden fault is an important fault in Colorado, with a forecasted economic loss of $22 billion resulting from a 6.5 magnitude earthquake (DOLA 2007). The potential magnitude of physical and economic loss from the Golden fault dictates that it should be considered in the list of stressors that pose a threat to the Denver Region.

HAZUS offers three ways to define an earthquake scenario: using an historical epicenter event, a source event (i.e. ,fault line), or an arbitrary event. The historical epicenter event option was used for simulating the Rocky Mountain Arsenal earthquake example, and an arbitrary event used for an event that could potentially occur along the Golden fault line. Typically, the source event option would better suit the later scenario along the Golden fault line, however, there are only three Colorado faults existing in the source event database in HAZUS, and these do not include the Golden fault (shown in Figure 7.72).



Source Event Database

Define the fault event for the Source Event option. Right click for Sort and Map options

Source Events:

eqFaultId	StateID	FaultName	MaxMagnitu	Characti
95	CA	Death Valley-graben	7.1	7.1
96	CA	Death Valley-south	7.1	7.1
97	CA	Panamint Valley	7.4	7.4
99	CA	Independence	7.1	7.1
579	CO	Cheraw Char. f 1/2 wt	7	7
625	CO	Northern Sangre de Christo fault	7.5	7.5
713	CO	Southern Sawatch fault	7	7
659	ID	Lost River fault	7	7
660	ID	Lemhi fault	7	7
661	ID	Beaverhead fault	7	7

Figure 7.72: Existing fault lines in Colorado pre-defined in the source event database in HAZUS

Specific information detailing the Golden Fault was provided by the Colorado Geological Survey, including: cumulative length, average strike orientation, and dip angle (Kirkham 2007). The location of the epicenter was determined by mapping a GIS file of the Quaternary Fault and Fold Database of the United States in ArcGIS provided by USGS, and placing the epicenter near the center of the Golden fault line. The fault line was constructed in HAZUS-MH based on the cumulative length and orientation from the Colorado Geological Survey report. Figure 7.73 below shows the actual Golden Fault line from the Quaternary Fault and Fold Database, and the representative fault line used in HAZUS-MH for the earthquake simulation.

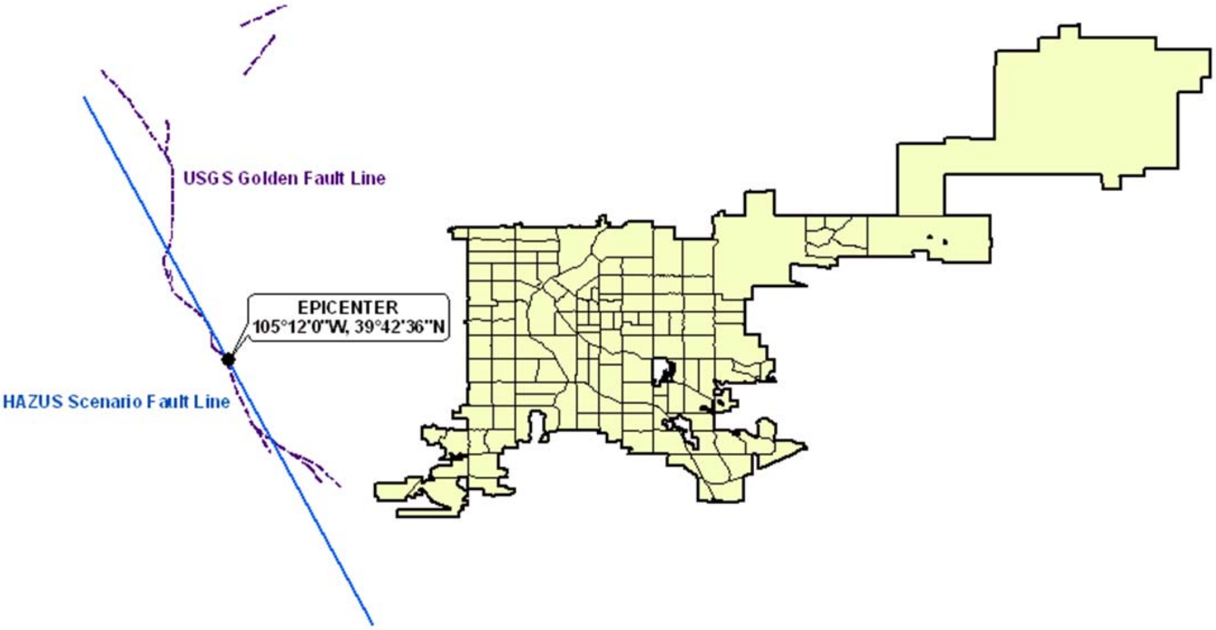


Figure 7.73: Actual and representative Golden Fault line

The Golden fault exhibits a reverse-slip mechanism, in which the rock above the fault moves in an upward direction, and has a dip angle of greater than forty-five degrees (USGS 2011). The reverse-slip is the fault type specified in the HAZUS model in this study. Figure 7.74 below demonstrates this behavior:

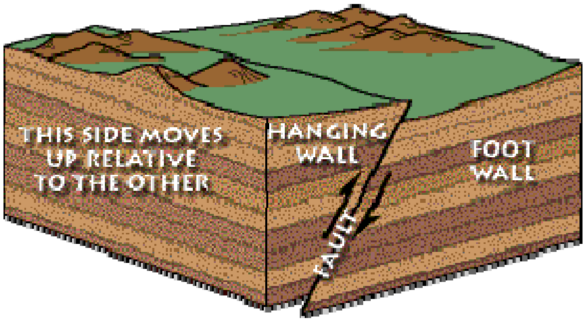


Figure 7.74: Reverse-slip fault behavior (provided by geomaps.wr.usgs.gov)

Using the Golden fault information provided by Colorado Geological Survey and the Quaternary Fold Database, the input parameters shown in Table 7.2 were specified to represent an actual earthquake event resulting along the Golden fault line.

Table 7.2: Input parameters for Golden fault line earthquake scenario

Golden Fault Line Earthquake HAZUS-MH Input Parameters	
moment magnitude	6.5
longitude of epicenter	-105.20
latitude of epicenter	39.71
depth (Km)	10
width(Km)	10
rupture length (sub surface) (Km)	39.00
rupture length (surface) (Km)	39.00
rupture orientation (degrees)	157 º
dip-angle	70º
attenuation function	WUS Shallow Crustal Event – Non Extensional
fault type	Reverse-slip

7.2.4 Golden Fault Earthquake Scenario Results

The following results presented from the Golden Fault earthquake scenario are more condensed than the results shown for the Rocky Mountain Arsenal earthquake scenario due to unnecessary repetitiveness. The results provided highlight the key information.

Casualties and Shelter Requirements:

In the event of a 6.5 magnitude earthquake located along the Golden Fault line, HAZUS estimated three different casualty estimates based on the time of day (2:00 AM, 2:00 PM, and 5:00 PM) to be 68, 153, and 112 respectively. Figure 7.75 below depicts where the casualties are located based on the maximum casualty count at 2:00 PM.

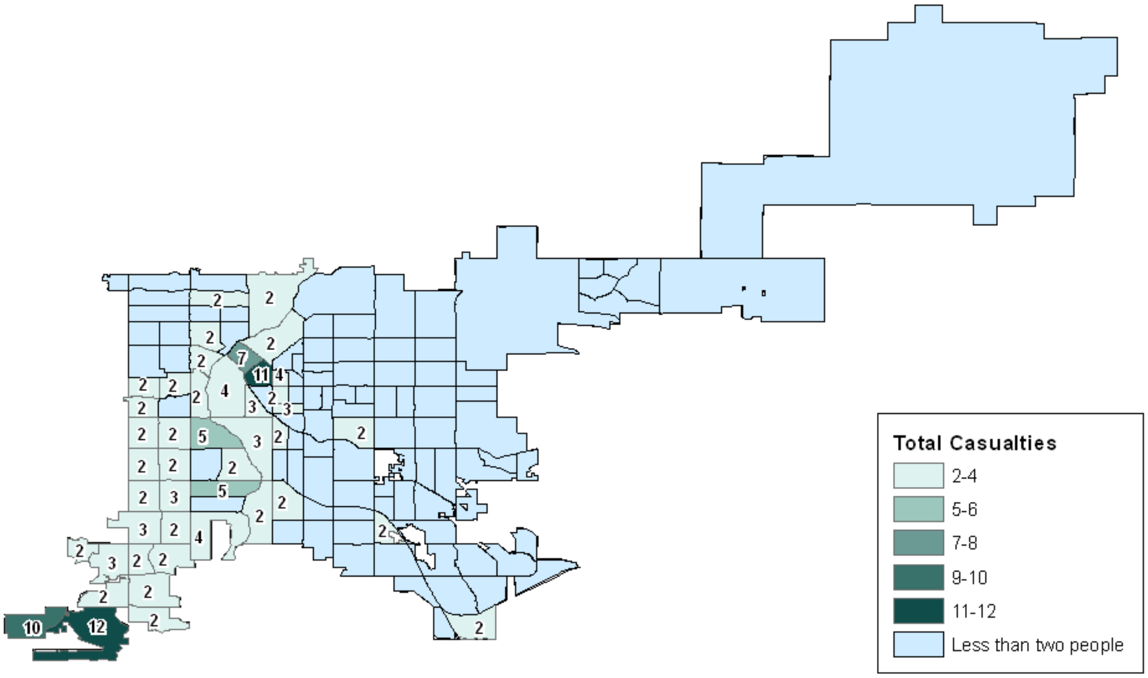


Figure 7.75: Casualties at 2:00 PM due to magnitude 6.5 Golden Fault line earthquake scenario

The above figure shows 12casualties in the census tract nearest to the epicenter of the earthquake scenario in the southwest part of the region. The tract with the second highest number of casualties is however located farther away from the epicenter near the downtown area, similar to the Rocky Mountain Arsenal earthquake scenario. Figure 7.76 & 7.7 below, look more closely at the most vulnerable locations in terms of number of casualties.

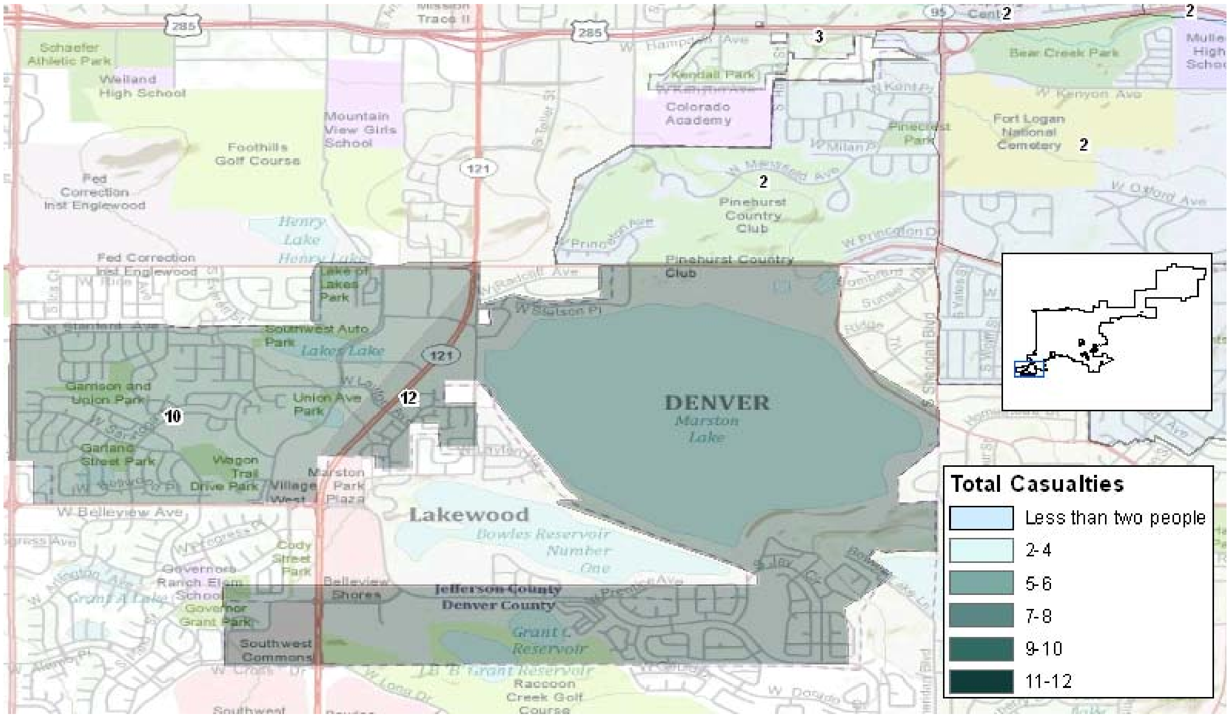


Figure 7.76: Tracts with high casualty numbers nearest to earthquake epicenter

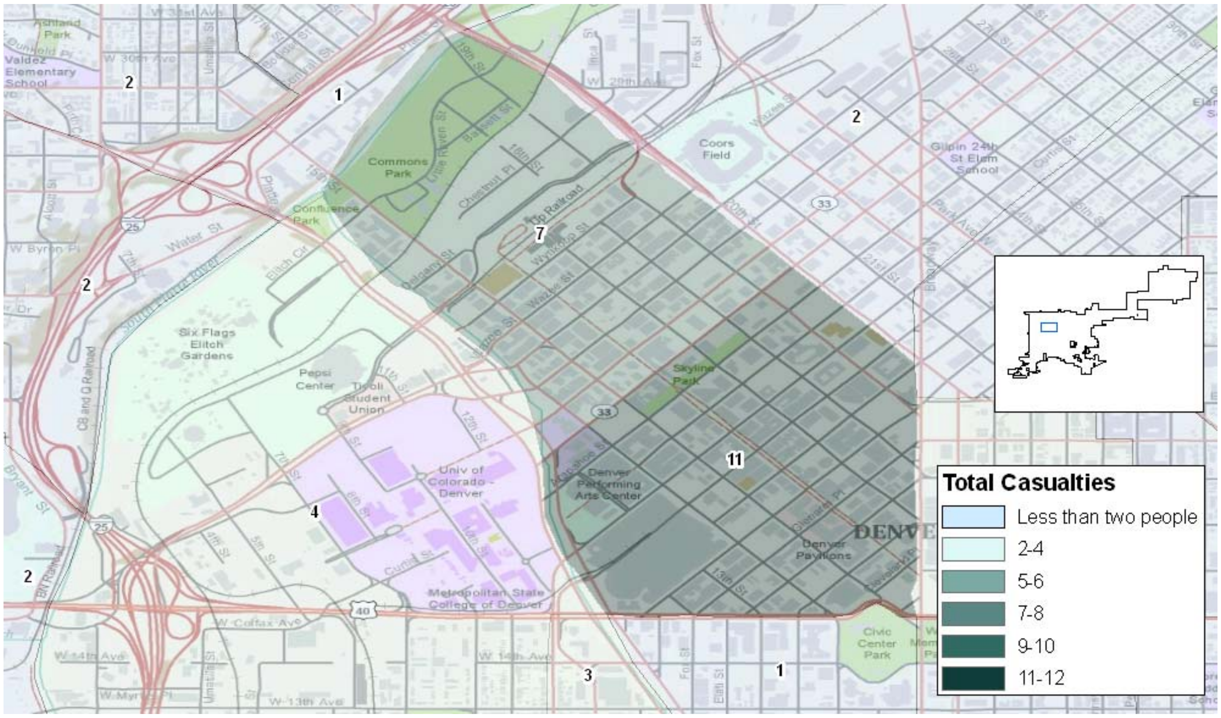


Figure7.77: Tracts with high casualty numbers near downtown

In this scenario, HAZUS estimates that there are a total of 7,436 displaced households. 4,675 of these displaced households will require public temporary shelter. These estimated figures can help prepare an inventory of this many beds for this type of situation. The number of short term shelter needs and number of displaced households per tract are shown in figures 7.78 & 7.79 below.

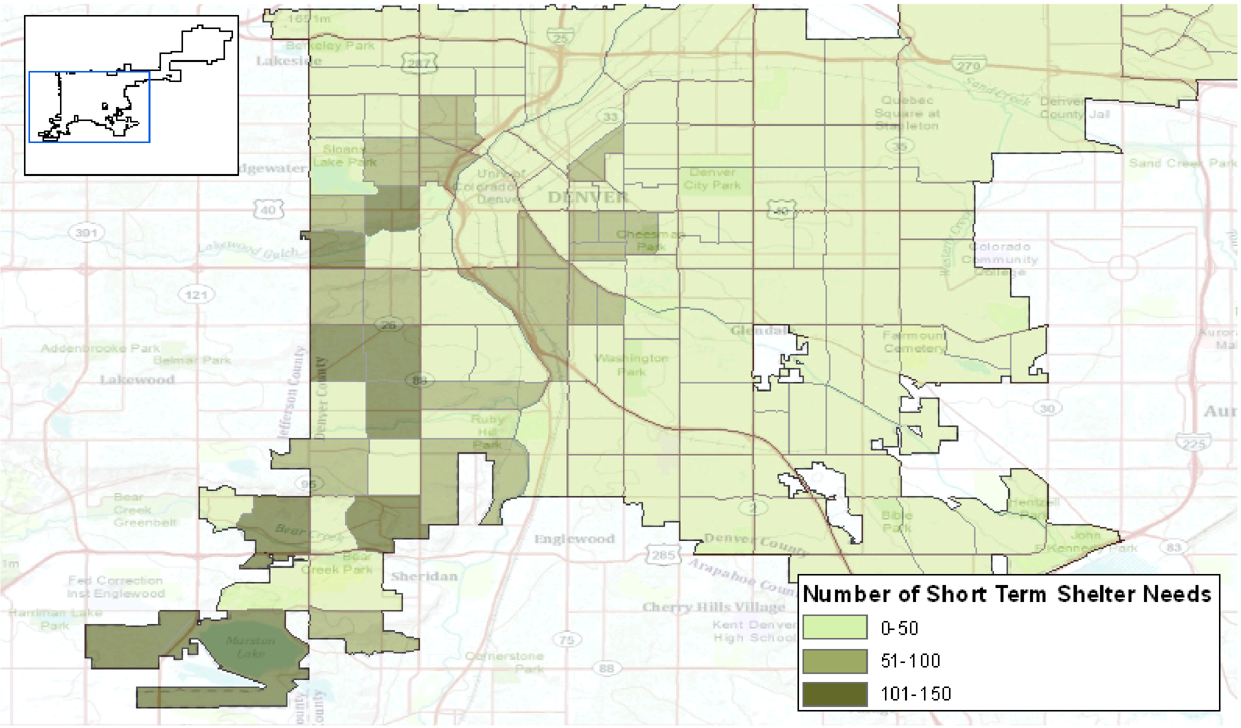


Figure 7.78: Number of short term shelter needs per census tract

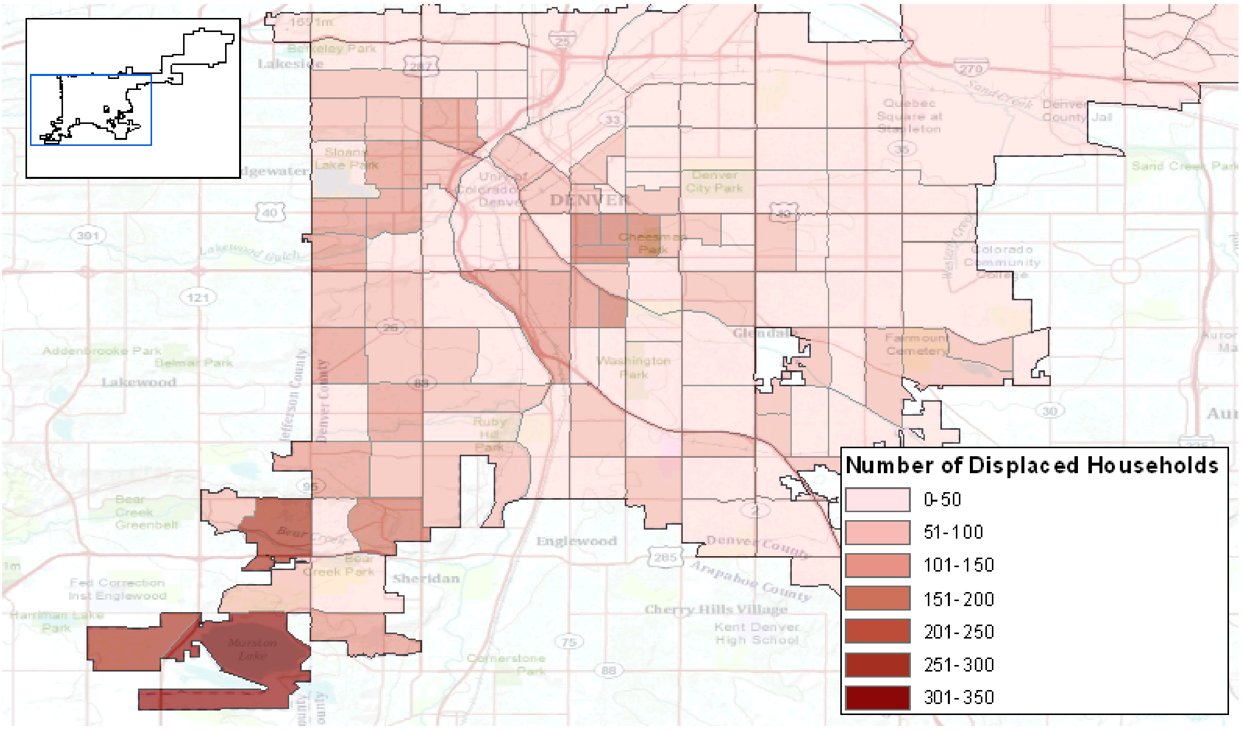
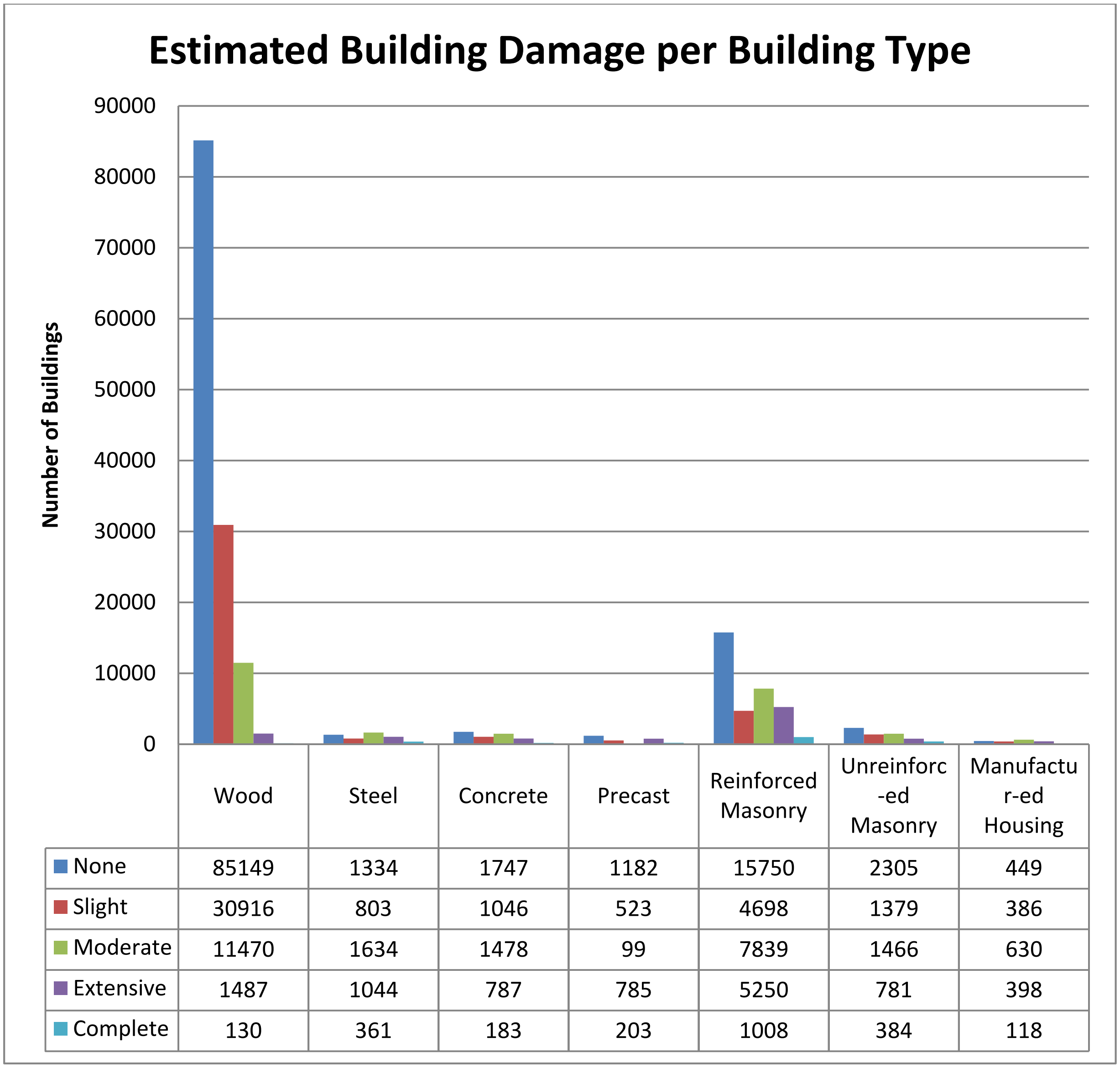


Figure 7.79: Number of displaced households per census tract

Estimated Building Losses:

The 6.5 magnitude Golden Fault line earthquake caused 38,431 of the total 186,000 buildings in the region to be moderately damaged, and 2,385 damaged beyond repair. Figure 7.80 shows the expected building damage by building type:



	Wood	Steel	Concrete	Precast	Reinforced Masonry	Unreinforc-ed Masonry	Manufactu r-ed Housing
None	85149	1334	1747	1182	15750	2305	449
Slight	30916	803	1046	523	4698	1379	386
Moderate	11470	1634	1478	99	7839	1466	630
Extensive	1487	1044	787	785	5250	781	398
Complete	130	361	183	203	1008	384	118

Figure 7.80: Estimated building damage for each building type

The numbers for each building type for each level of severity of damage further support that un-reinforced masonry buildings in the Denver Region result in the most extensive and complete building damage even though a majority of the structures built in the region are of wood construction. This is again based on the percentage of buildings completely damaged out of the total number of buildings per specific building type. The same conclusion can be made as in the Rocky Mountain Arsenal earthquake scenario, that retrofitting applications for reinforced masonry buildings should be utilized.

The building damage losses total building losses for all the building type categories yield similar results as in the Rocky Mountain Arsenal earthquake scenario (seen in figures 7.81 and 7.82). Both earthquake scenarios resulted in significant damage in the central part of the Denver Region, again located where there are both social and physical vulnerabilities and critical infrastructure elements. The total building losses shown in figure 7.81 also show substantial economic loss in the tract located near Rocky Mountain Arsenal (northeast of central Denver).

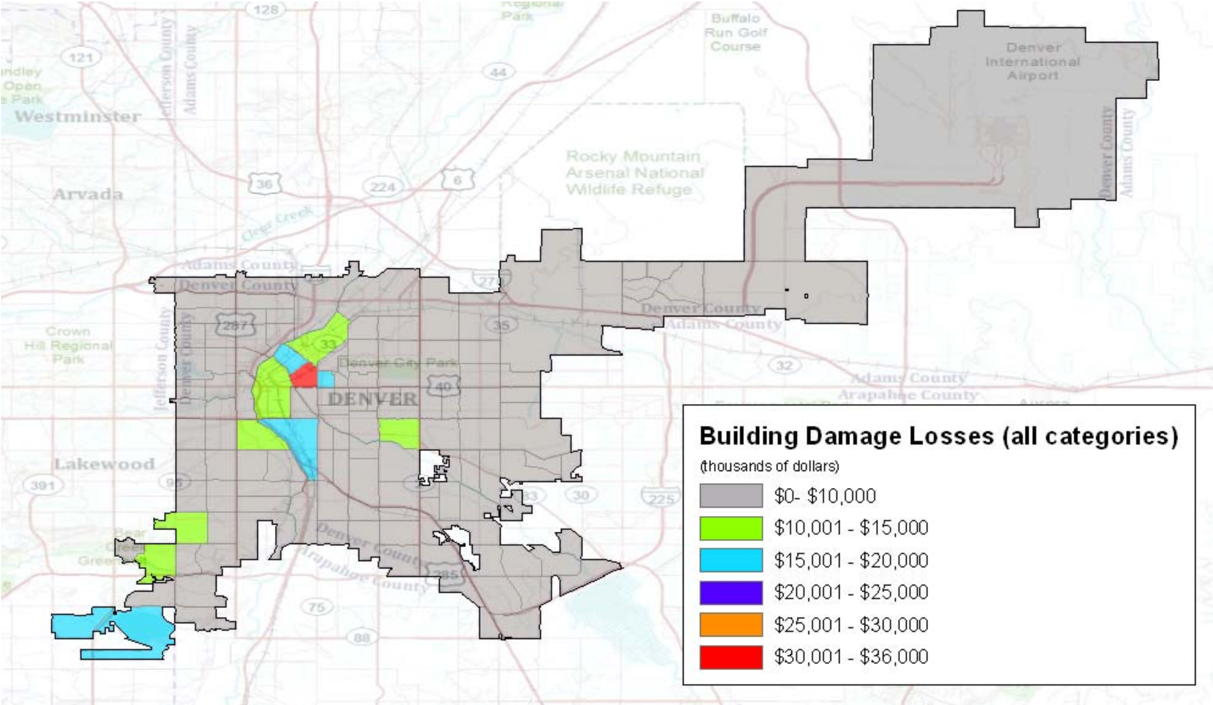


Figure7.81: Building damage losses for all building type categories caused by the Golden Fault earthquake scenario

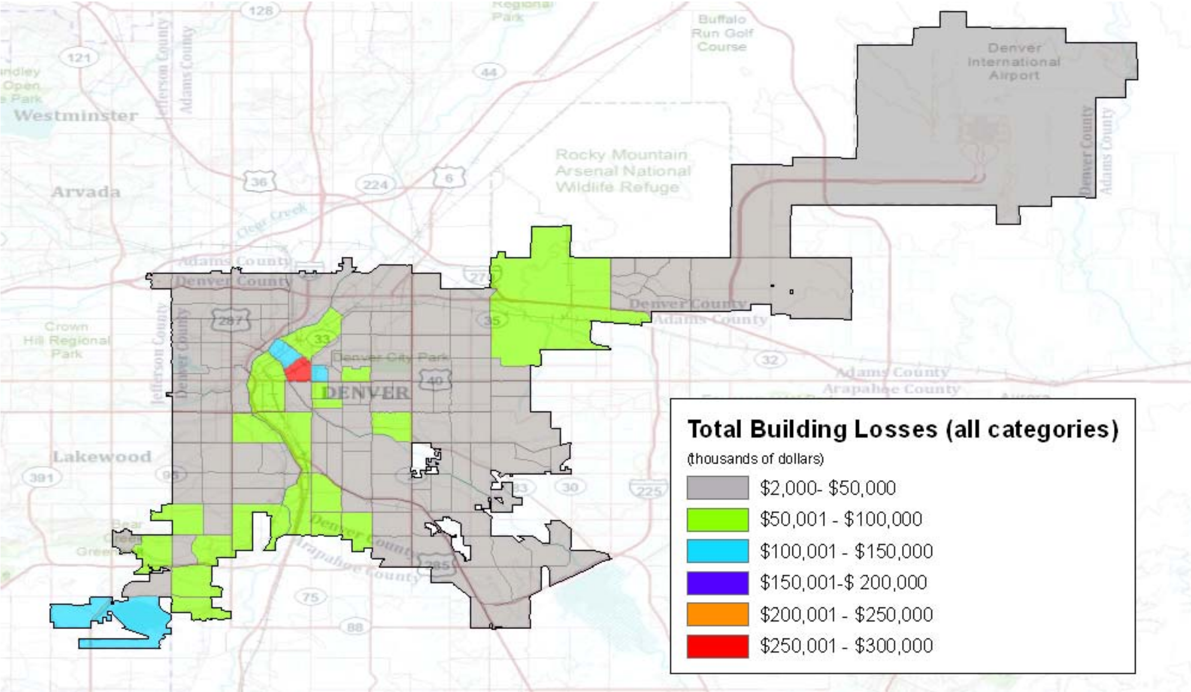
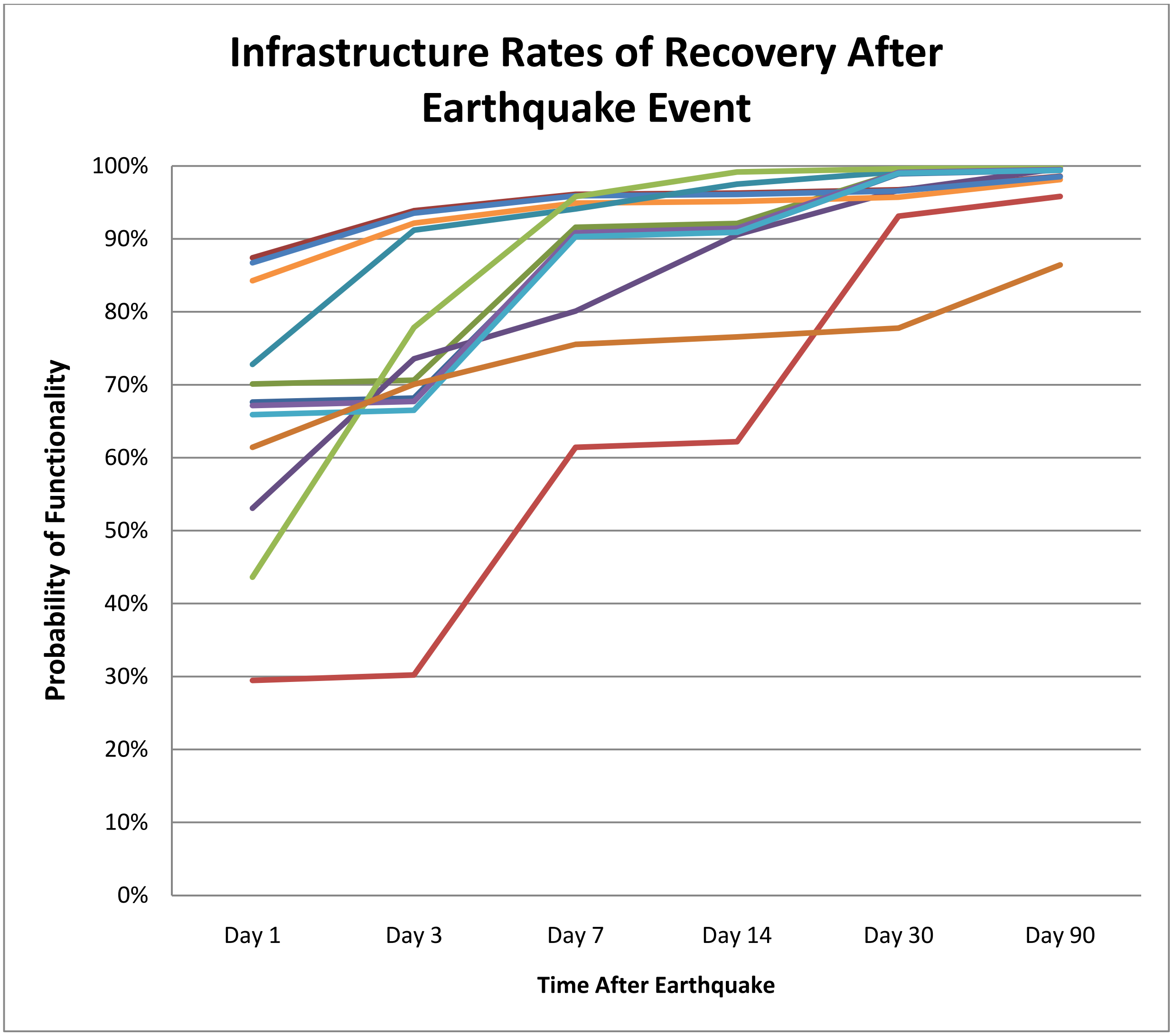


Figure 7.82: Total building losses for all building type categories caused by the Golden Fault earthquake scenario

The rates of recovery after the event of a magnitude 6.5 earthquake along the Golden Fault again show hospitals as having the longest recovery period extending over thirty days to reach 90% functionality. Other facilities/critical infrastructure elements with long recovery rates include oil facilities and highway bridges. Some of the facilities with a faster recover rate are communication facilities, bus facilities, and light rail segments. All of these recovery rates can be seen in figure 7.83 below.



	Day 1	Day 3	Day 7	Day 14	Day 30	Day 90
— School Facilities (217)	67.63%	68.16%	90.43%	90.97%	98.92%	99.39%
— Railway Facilities (10)	87.41%	93.86%	96.11%	96.28%	96.73%	98.58%
— Police Station Facilities (17)	70.11%	70.62%	91.60%	92.12%	99.11%	99.49%
— Oil Facilities (7)	53.07%	73.56%	80.10%	90.57%	96.64%	99.66%
— Light Rail Segments (28)	84.27%	92.15%	94.90%	95.14%	95.71%	98.12%
— Bus Facilities (6)	86.72%	93.52%	95.90%	96.08%	96.57%	98.52%
— Hospital Facilities (14)	29.46%	30.21%	61.41%	62.19%	93.11%	95.82%
— Communication Facilities (2)	72.80%	91.20%	94.10%	97.50%	99.20%	99.80%
— Electrical Power Facilities (4)	43.63%	77.85%	95.80%	99.18%	99.60%	99.90%
— Emergency Operations Facilities (2)	67.15%	67.70%	90.85%	91.45%	99.10%	99.50%
— Fire Station Facility (1)	65.90%	66.50%	90.30%	90.90%	99.00%	99.40%
— Highway Bridges (16)	61.41%	70.07%	75.53%	76.56%	77.76%	86.42%

Figure 7.83: Critical infrastructure rate of recovery for Golden Fault Earthquake scenario

What can be learned from examining these two earthquakes with their epicenters located at on different sides of the Denver Region boundary is that similar results were found. This shows that efforts conducted by city planners and especially emergency personnel can be more concise. Observing several hazard scenarios and identifying repeating locations showing significant damage can help allocated resources to more vulnerable areas, allowing for more cost-benefit solutions to be made

7.3 Transportation of Hazardous Materials

Hazardous material transportation using roadway systems has become a worldwide issue, and the Denver Region is no exception. As mentioned previously, one of Denver's hazmat units, HAMER 1, was "listed as the team with the most hazmat responses in the country in 2005...and was second in 2006" (Burke 2007). The transportation of hazardous materials on major corridors directly through the heart of Denver poses a risk exposing human lives (Denver is ranked the 26th most populous city according to the 2010 Census) along with extensive physical and economic damage.

Colorado has provided specific restrictions with some designated routes allowing hazardous material and others permitted for both hazardous and nuclear materials. Several of these routes traverse through the Denver Region along two main interstate highways: Interstate-25 and Interstate-70. Each of these highways has close proximity to dense populations, vulnerable populations, critical facilities, several EPA facilities and critical infrastructure, as well as serving as main corridors within the region's transportation system. The 2011 Colorado designated hazardous and nuclear material routes can be seen in Figure 7.84.

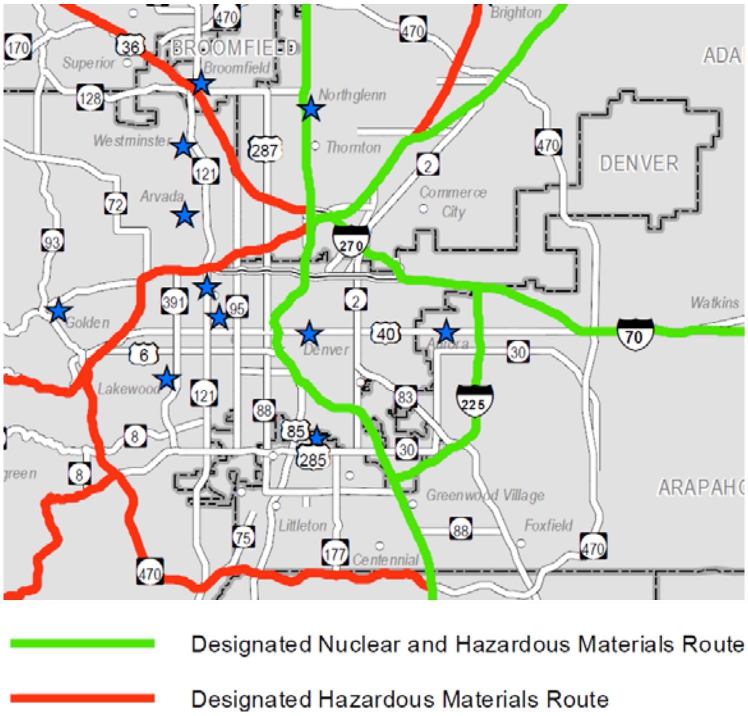


Figure 7.84: Colorado's 2011 hazardous and nuclear materials route restrictions (provided by the Colorado Department of Transportation Division of Transportation Development)

Both designated interstates for transporting hazardous materials through the Denver Region, are also designated routes for nuclear materials. Although the transportation of nuclear materials poses a risk, the probability of a nuclear material being released due to a highway accident is very low. There are two types of containers used to transport hazardous materials: a Type A container designed to "survive normal transportation handling and minor accidents", and a Type B container "able to survive severe accidents" (USNRC 2010). The container type is specified by the amount of radioactive material. Type A containers are for lower quantities of radioactive material and are typically a fiberboard box, wooden crate, or metal drum, where as Type B containers contain greater amounts of radioactive material and are in a special shielded transport container with an outer drum and an inner containment vessel separated by thermal insulation. According to the United States Nuclear Regulatory Commission Technical Training Center (USNRC 2010), only one percent of several accidents involving a vehicle carrying hazardous materials in a Type A container have failed. Several accidents involving the transportation of a Type B package have occurred, with only one documented case of a package failure (involving an industrial radiography source) (USNRC 2010). Due to the low probability of an accident resulting in the release of a nuclear material, this study will focus on hazardous material related accidents containing liquefiable petroleum gas (LPG).

LPG is a highly flammable material causing damage to surrounding areas due to extensive heat radiation and overpressure. Blast overpressure is the result of a high energy impulse producing waves which can result in “injury predominantly to the hollow organ system such as auditory, respiratory, and gastrointestinal systems” (Elsayed & Gorbunov 2006). Overpressure can also result in building damage including structural damage in close range and broken windows farther from the blast location. A study performed by Chakrabarti and Parikh investigating the impact zone from flammable and toxic release determined that the heat radiation due to an accident involving a LPG bulk transport vehicle can affect an area up to approximately 4,242 feet (1293 meters) in diameter. The radial distance experiencing the most thermal radiation is about 1,050 feet (320 meters). The explosion overpressure can affect an area up to 2,815 feet (858 meters) in diameter, with a critically affected area of 843 feet (257 meters) (Chakrabarti & Parikh 2010).

A similar study was performed by Ayyub, Markham, and Chang in “Development of Spatial Risk Profiles of Cargo Rail Systems”, focused on understanding the risk due to cargo rail systems carrying hazardous materials through populated areas. That study examined the population and property affected by specified influence areas along the railway route, creating a risk profile for a particular rail segment to determine specific locations where the consequences are most significant. The influence areas used were defined by four different radii ranging between 492 feet (150 meters) and 1,969 feet (600 meters) (accounting for the decreasing intensity of damage the further away from the centroid of the explosion) (Ayyub, Markham & Chang 2011). The focus of the following section is an analysis on the effect of a tank truck accident carrying LPG along the designated travel route through Denver, Interstate-25, specified by the Department of Transportation. Based on the two studies previously mentioned, the two radii used for influence areas are 1,000 feet (305 meters) and 2,000 feet (610 meters). The smaller influence area (1,000 feet radius) represents an area in which the entire population is counted as casualties and all assets are fully damaged and no longer operable. The larger influence area (2,000 feet radius) extending past the inner influence area represents an estimated fifty percent damage.

In the following study, five specific locations where chosen as examples of the types of key areas where a detailed analysis should be performed by local administrations to aid in developing emergency preparedness plans and reducing levels of vulnerability. These locations are characterized by an area containing: a dense population, a vulnerable population, proximity to critical facilities, near major railroads, and a location with a high daily traffic count (figure 7.85). Budget permitting, a thorough analysis should be conducted, in which local administrators would investigate along an entire route where hazardous materials are being transported. This would provide insight to the potential damage that could occur at any location along these designated routes.

(1) Densely populated area

(2) Vulnerable population

(3) Proximity to critical facilities

(4) Route with high traffic count

(5) Near major railroads

Figure 7.85: Locations of five scenarios along Interstate-25 depicting hazardous material accidents

7.3.1Hazardous Material Scenario Results

Location 1: Densely Populated Area

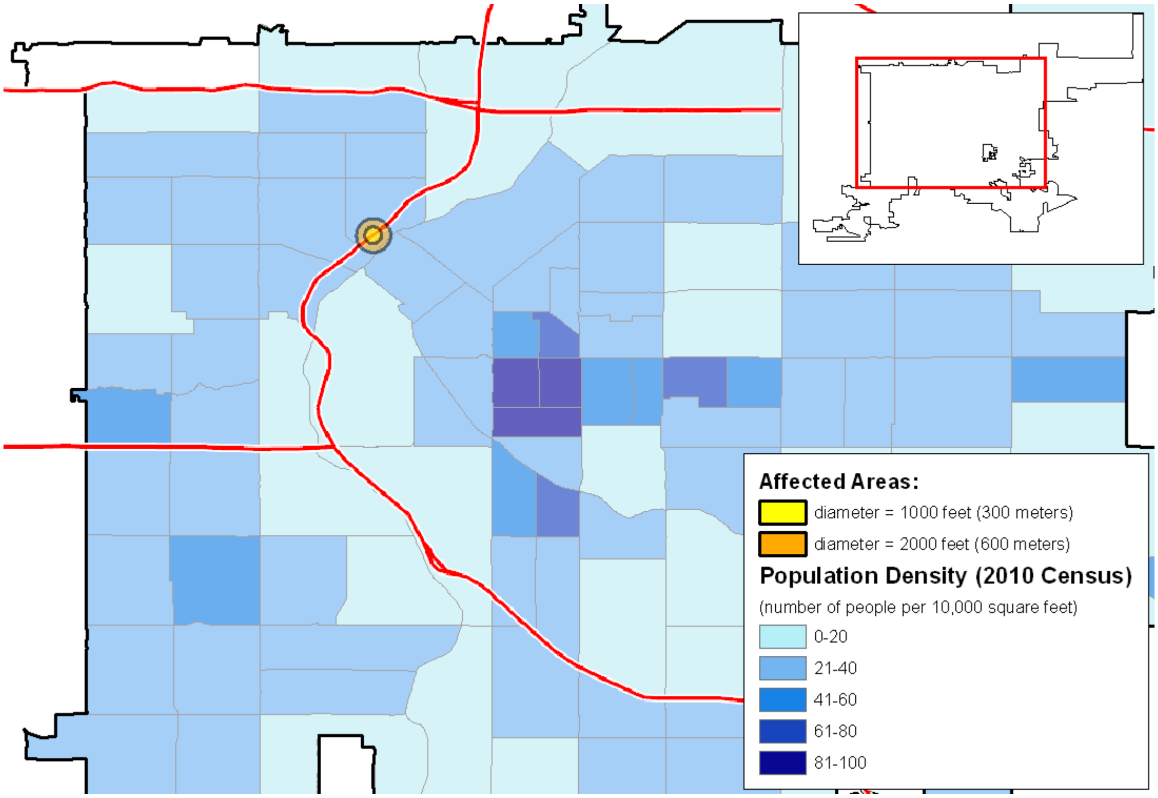


Figure7.86: Scenario located in densely populated area

The first scenario recognizes that there are residential areas adjacent to Interstate-25, exposing many lives in the event of an accident involving hazardous materials. Fortunately, the areas in the Denver Region with the highest population density do not intersect with this route, but are instead offset by a far enough distance to avoid the effects caused by an explosion resulting from the ignition of a highly reactive material. In the case scenario depicted in figure 7.86 above, the estimated number of casualties due to an explosion is between 1000 and 2500. This estimate does not include any fatalities due to vehicle accidents on the highway caused by the disruption. Figure 7.87 below is a closer view of location (1) showing nearby essential facilities which could possibly be affected by the incident.

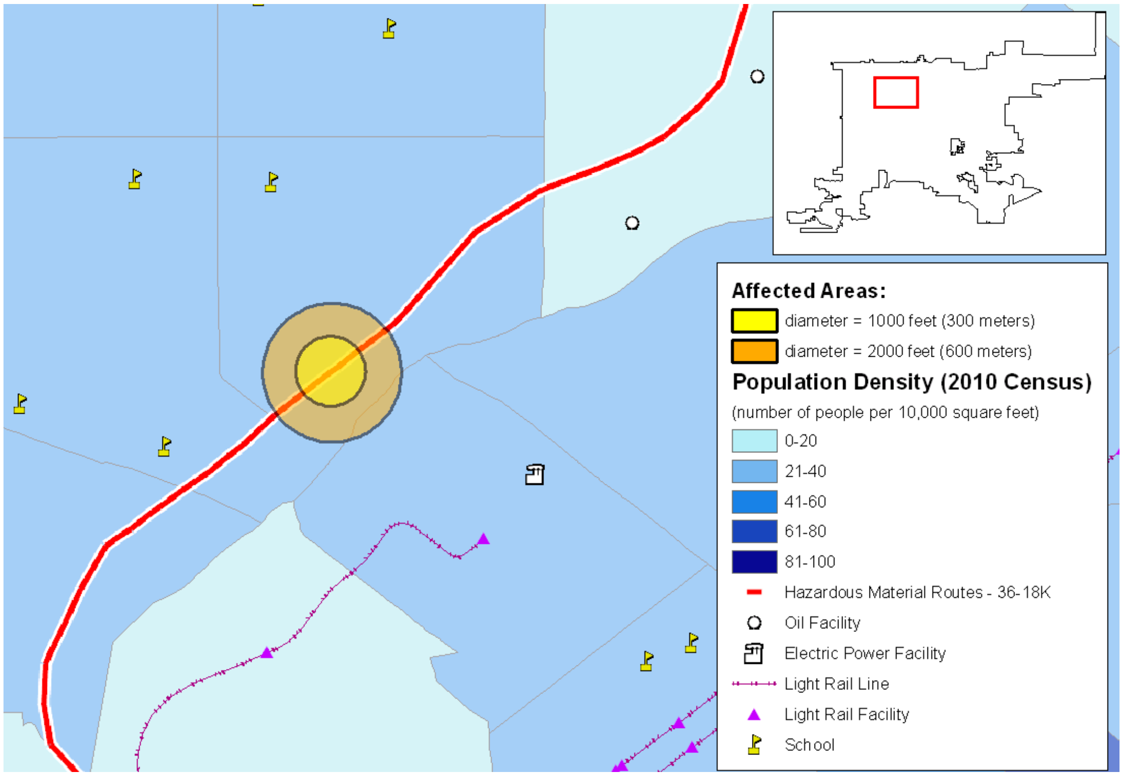


Figure 7.87: Proximity to essential facilities for location (1)

In observing the locations of essential facilities in respect to the affected areas resulting from the hazardous materials accident, it can be seen that several are near possible harm. For instance, if the incident were to occur more southbound on Interstate-25, one school would be directly in the affected area. Several other schools nearby could also be affected and require evacuation. If the hazardous material contained a high enough level of toxicity, many children at this location would be affected. In another situation, if the accident occurred northbound from the location shown, an oil facility would be directly impacted. Depending on the magnitude of impact caused by the thermal load and overpressure from the accident, the oil facility could possibly be shut down. This scenario would not only greatly affect the functionality of the transportation system by eliminating accessibility along one of Denver's major highway corridors, but could also translate to a disruption of the light rail line. Even if the line is not physically damaged, due to safety precautions, operators may be required to temporarily stop the line.

Location 2: Vulnerable Population

The second scenario is located in an area where social vulnerability exists based on poverty level and race. The percentage of the population below the poverty level in the area where the hazardous material accident scenario is located is 60-80% (see figure 7.88). Areas where the average income is extremely low are typically the areas that experience the most difficultly in recovering from a disastrous event, as described in the following quote from *Vulnerability of Cities* by Mark Pelling:

> *"For low-income households, labour, tools and the dwelling will be most critical and are also the most liable to loss during disaster. Loss of these assets through environmental factors (or other shocks or stresses) will cause the income earning capability of the household to fall and lower the range of entitlements to which household members can make claim, making the household and its members more vulnerable to any subsequent everyday or catastrophic stresses or shocks"* (Pelling 2003).

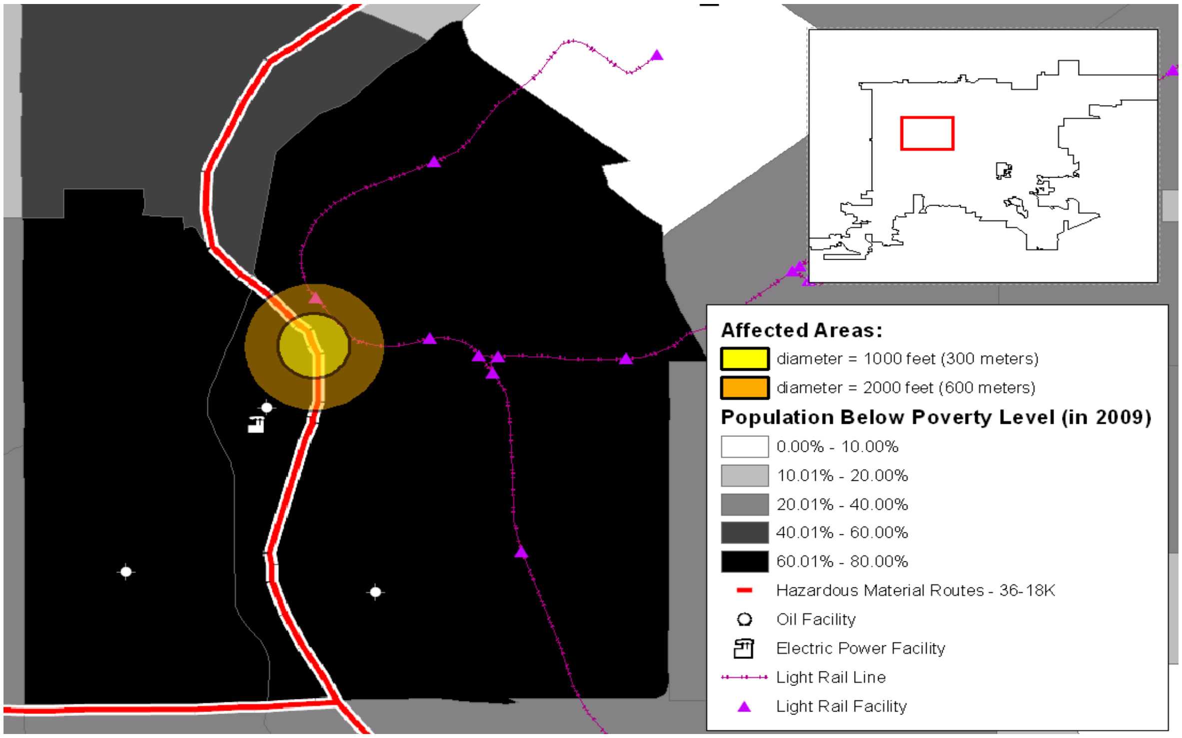


Figure7.88: Location (2) in an area where majority of the population is below the poverty level

This location is predominantly of Hispanic and Latino ethnicity. Over the years, researchers have examined the ability for different types of groups of people to restore their community back to its original (or near original) state after a disastrous event (Enarson & Betty 1998). Race, amongst other characteristics, has been identified as one of the characteristics associated with this resiliency. Unfortunately, there is this social inequality that makes it more difficult for some communities to overcome different stressors than others. Some of the issues stemming from this include unemployment, language barriers, lack of education, and etc. Figure 7.89 shows location (2) in an area heavily populated by Hispanics and Latinos.

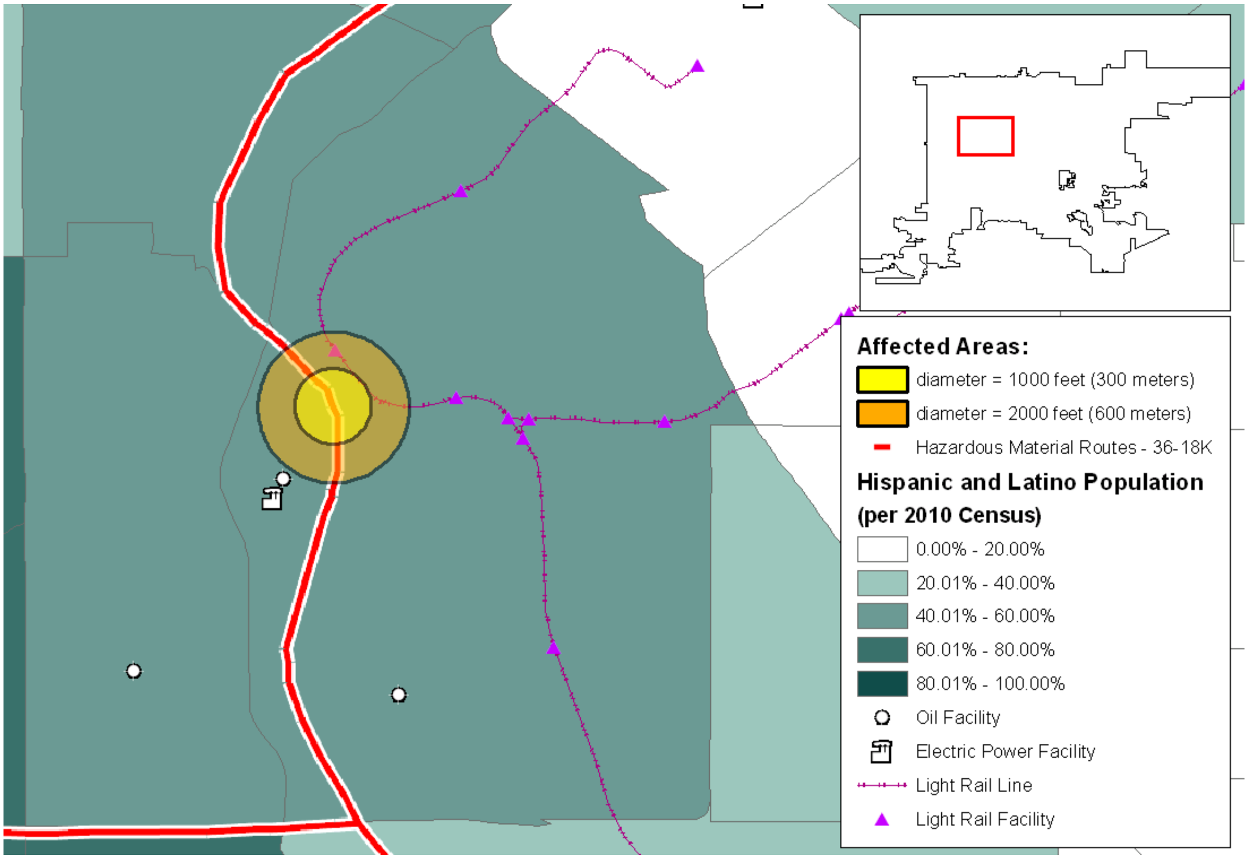


Figure7.89: Location (2) in an area dominated by the Hispanic and Latino population

Location (2) is interesting not only because it is in a socially vulnerable location, but also where the population is expected to increase between 500% and 900% over the next 25-year period (shown in figure 7.90). This is a dramatic increase in population, making it one of the most rapidly growing areas in the Denver Region. A high increase in population in a small location, along with a population well below the poverty level only increases the associated level of risk if a hazardous material related incident were to occur at this location. Furthermore, this location also has close proximity to the light rail line (including one light rail facility), as well as an oil facility and an electric power facility, showing an example of the interdependent relations within Denver's infrastructure system simply based on proximity.

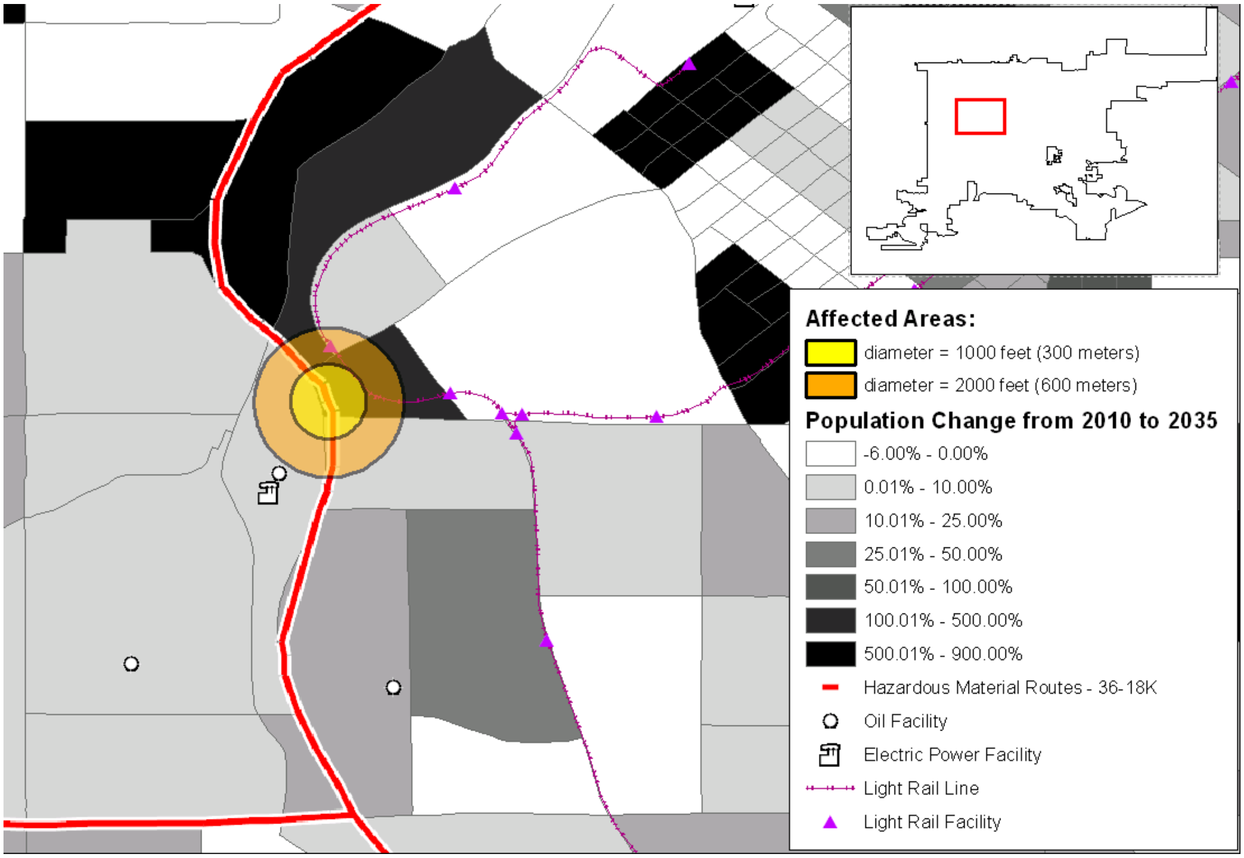


Figure 7.90: Hazardous material accident scenario located in area with an anticipated population growth of over 500% by 2035

Location 3: Proximity to Critical Facilities

The third location is slightly south from location (2), examining the proximity of the designated hazardous and nuclear material route to two critical facilities: an oil facility and an electric power facility (figure 7.91).

Figure 7.91: Critical facilities within affected area zones: an oil facility (Siegel Oil Company, right), and an electric power facility (Public Service Power Plant, left).

These facilities are located near Interstate-25 and Colfax Avenue, slightly south from several on and off ramps. Figure 7.92 shows the close proximity of these facilities to the interstate. An incident at this location would paralyze the highway and possibly shut down Colfax Avenue, another major transportation route. Figure 7.92 also displays that a part of Siegel Oil is located within the 1000 feet diameter affected area representing 100% damage. The Public Service Company power plant is only within the affected area defined by a 2000 feet diameter. Again, this scenario specifically involves liquefiable petroleum gas, therefore a possible scenario with a radioactive material would have a more serious outcome.

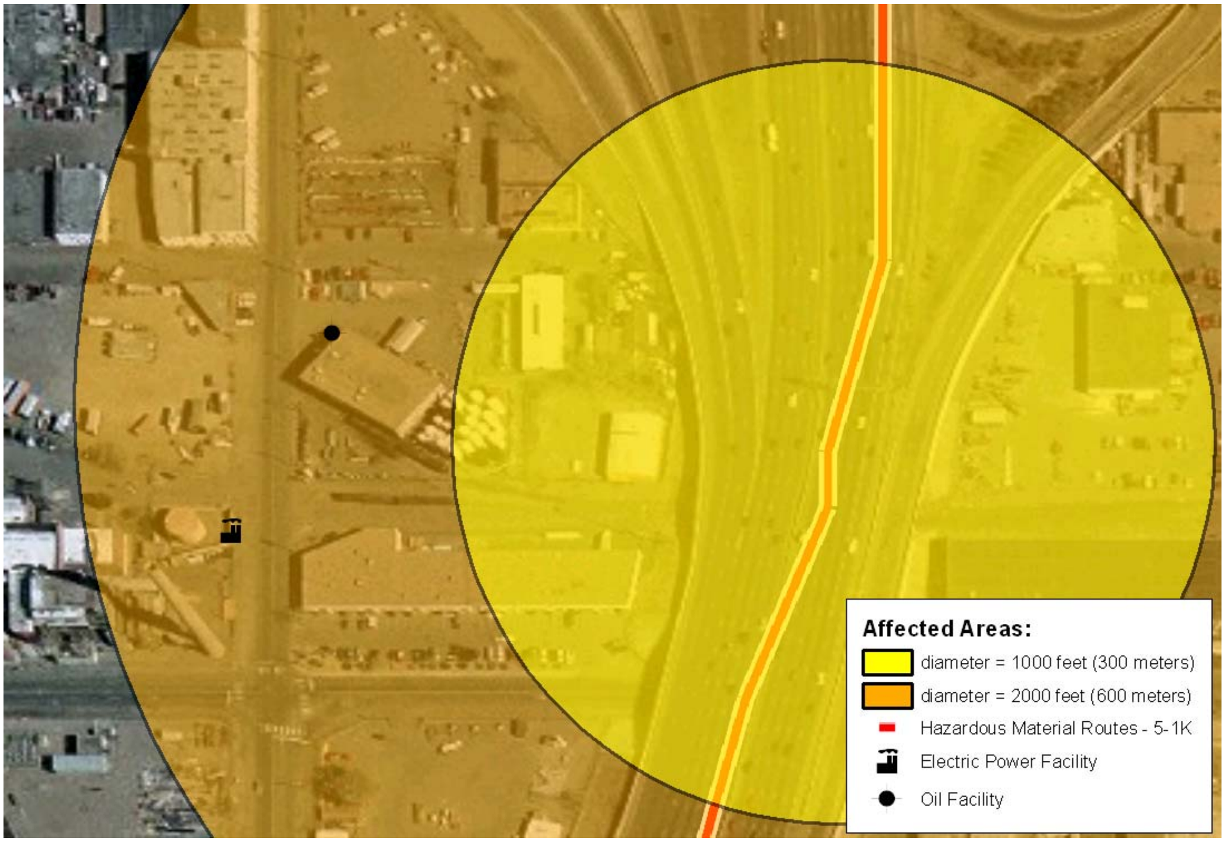


Figure 7.92: Affected areas overlapping with location of two critical facilities

Both of these facilities are critical in providing electricity and oil for nearby areas. Some of the locations nearby include Invesco Field (an arena used for professional football and other major events) seen in the upper-left in Figure 7.93 below, and the Auraria Campus for three universities in the upper-right corner. Interstate-25 is the main route used to both these locations, therefore a severe incident such as an accident involve a tank truck transporting LPG, would severely impact both these key locations. If the incident were to occur a short distance north of the current location shown in figure 7.93 below, Invesco Field itself could experience significant damage. Also, if a sports event or other event were taking place at the same time, the number of casualties and injuries would be much greater.

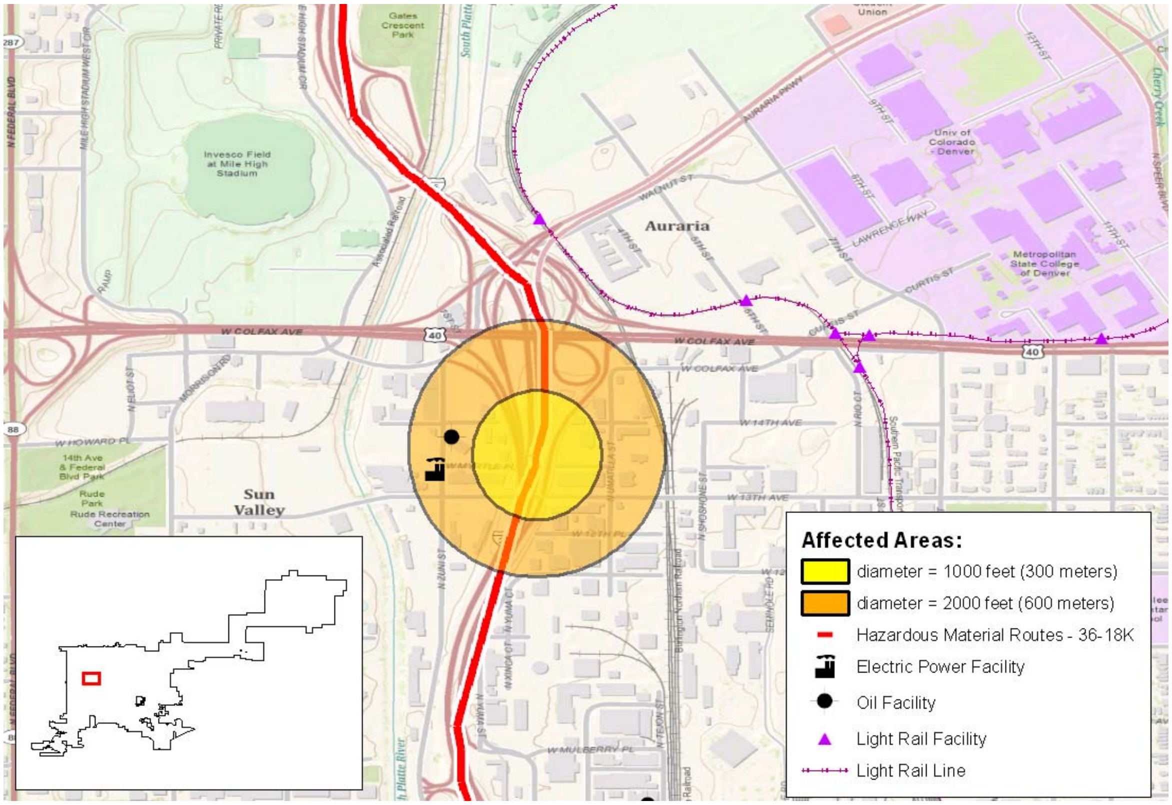


Figure 7.93: Hazardous material incident scenario at location (3) near two critical facilities and several key locations within the Denver Region

Another point to be made about this location is its proximity to a medical care facility, the Denver Health Medical Center. Although the location of the medical center is not within the boundary of the affected areas, the affected areas would likely eliminate any transportation routes traversing through the intersection of Interstate-25 and Colfax. These routes described are main pathways for emergency response operations, demonstrating vulnerability within the infrastructure system (figure7.94)

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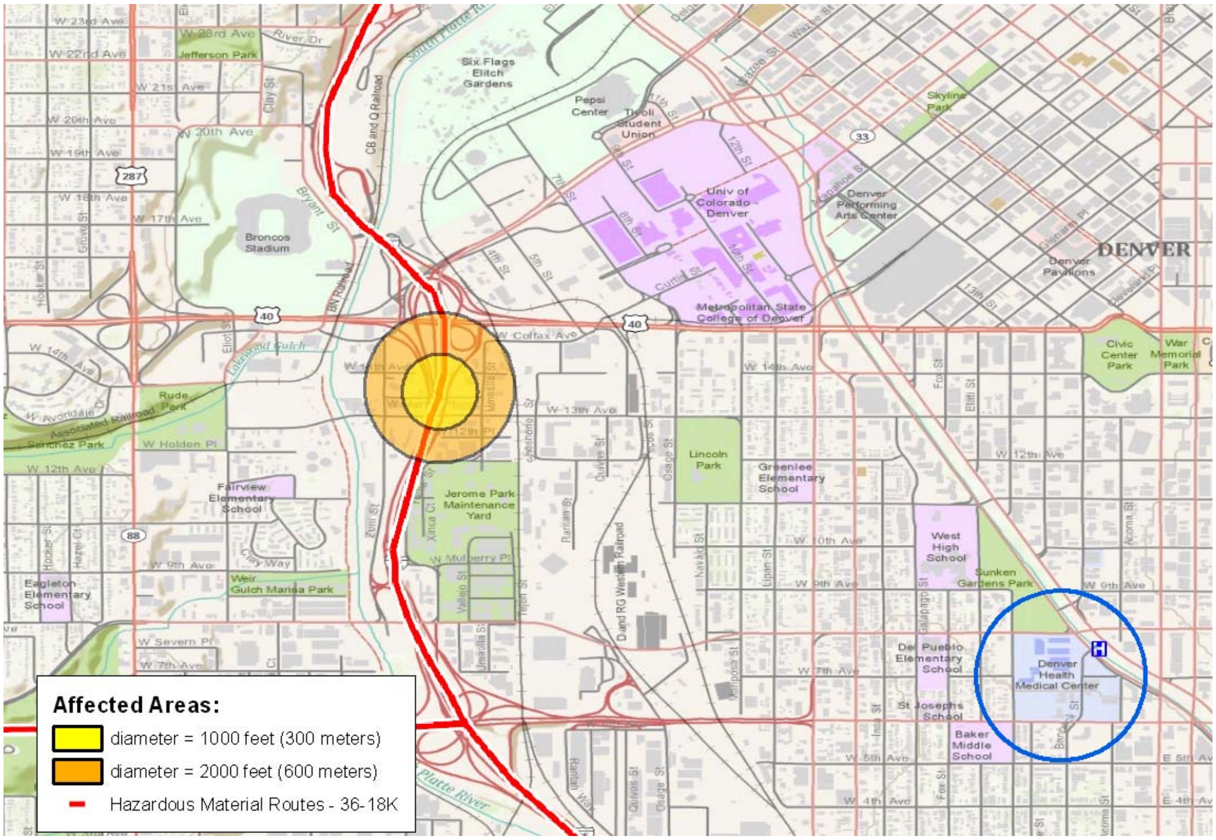


Figure 7.94: Location of medical center in relation to hazardous material incident at location (3)

In addition, as shown in figure 7.95 below, a majority of the facilities registered with the Environmental Protection Agency (EPA) are concentrated along both Interstate-25 and Interstate-70. Some of these agencies would probably not cause additional harm (e.g., Jackson Ice Cream Company adjacent to Interstate-25), but there are some EPA facilities that could potentially add to the already hazardous situation from accident involving a hazardous material (e.g., Colorado Paint Company along Interstate-70).

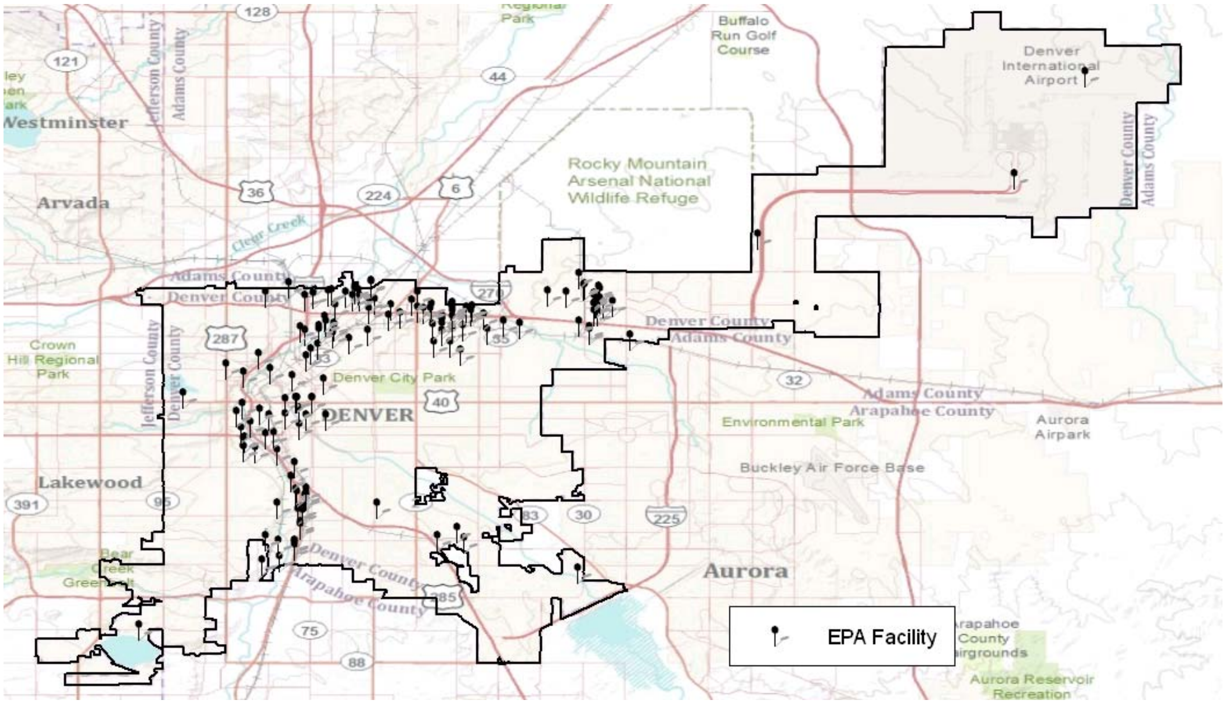


Figure 7.95: Concentration of EPA facilities alongside designated hazardous material routes, Interstate-25 and Interstate-70 (EPA facility data from U.S. Environmental Protection Agency)

Location 4: Route with High Traffic Counts

The fourth location was chosen based on the highest traffic count recorded in the Denver Region. Regional traffic data was provided by the Denver Regional Council of Governments (DRCOG) and then graphed in ArcGIS to determine the location of the highest traffic count. Figure 7.96 shows the various traffic counts recorded for the entire region, with the location of the highest traffic count (at Interstate-25 and Sixth Avenue) circled. This location was chosen because high traffic volume typically increases the probability of an accident.

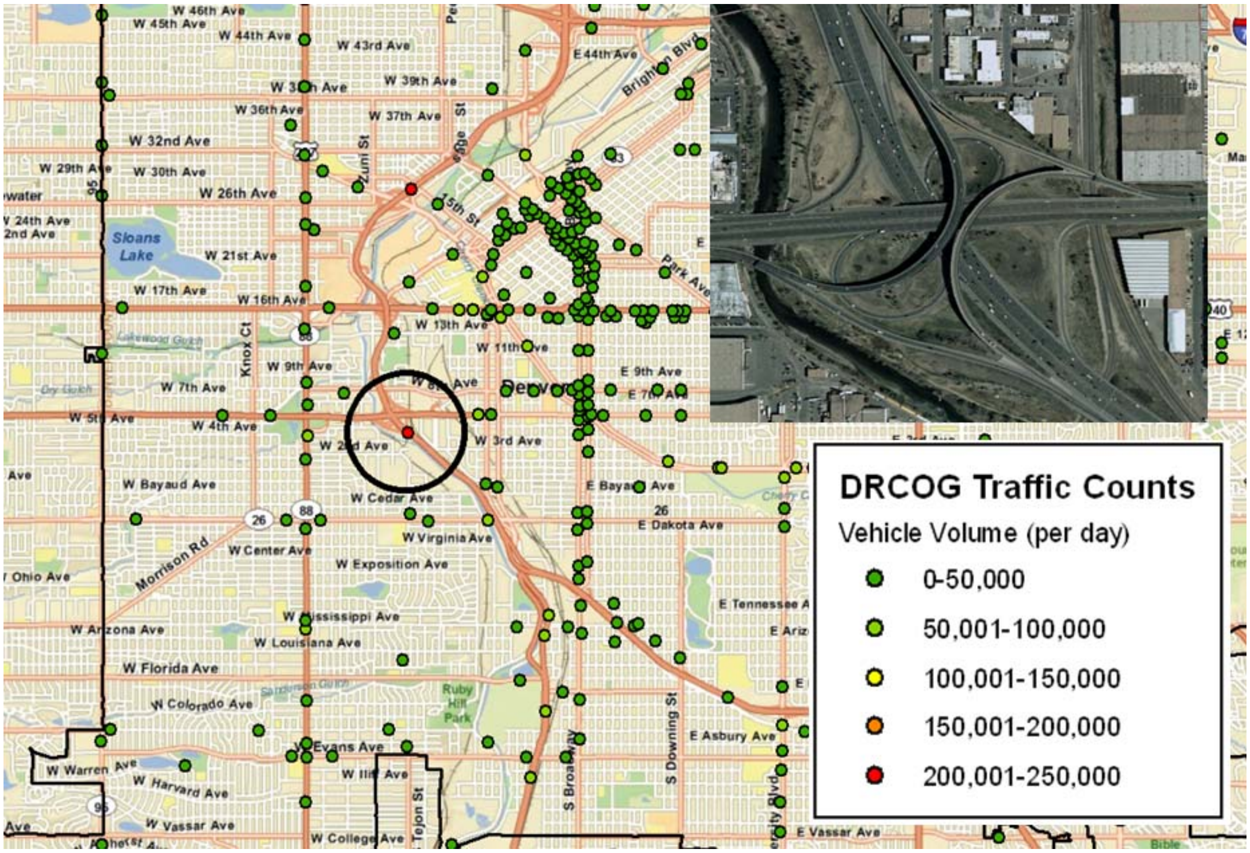


Figure 7.96: Regional traffic counts in the Denver Region, (highest traffic count circled)

The traffic count recorded at this station (located on Interstate-25 and 6th Avenue going northbound) reached 246,657 vehicles in one day (recorded in 2007) (DRCOG 2010). By the Colorado Department of Transportation designating the hazardous and nuclear material route along Interstate-25, a high level of risk is incurred by the region. If an incident involving a hazardous material, or much more a nuclear material, were to occur along this interstate, the Denver Region would experience extensive physical and economic damage. Physically, the number of casualties in the affected areas as well as the damage to the highway infrastructure itself would make recovery difficult. By severing this major corridor in the Denver Region, the city would likely become grid locked, emergency response would become increasingly difficult, the transportation of goods to and from regions to the north and south of Denver would cease, and businesses within the region would suffer resulting in substantial economic losses. As shown in the earthquake scenarios, the rate of recovery for highway bridges is quite low;

therefore the potential structural damage at this major intersection would affect Denver for several days. Naturally, if this incident were to occur affecting only this intersection, emergency repair efforts would be made to increase the rate of recovery to restore the transportation system back to its original state. Figure 7.97 also displays the loss of a major route used to reach the Denver Health Medical Center if an incident were to occur at or near this intersection.

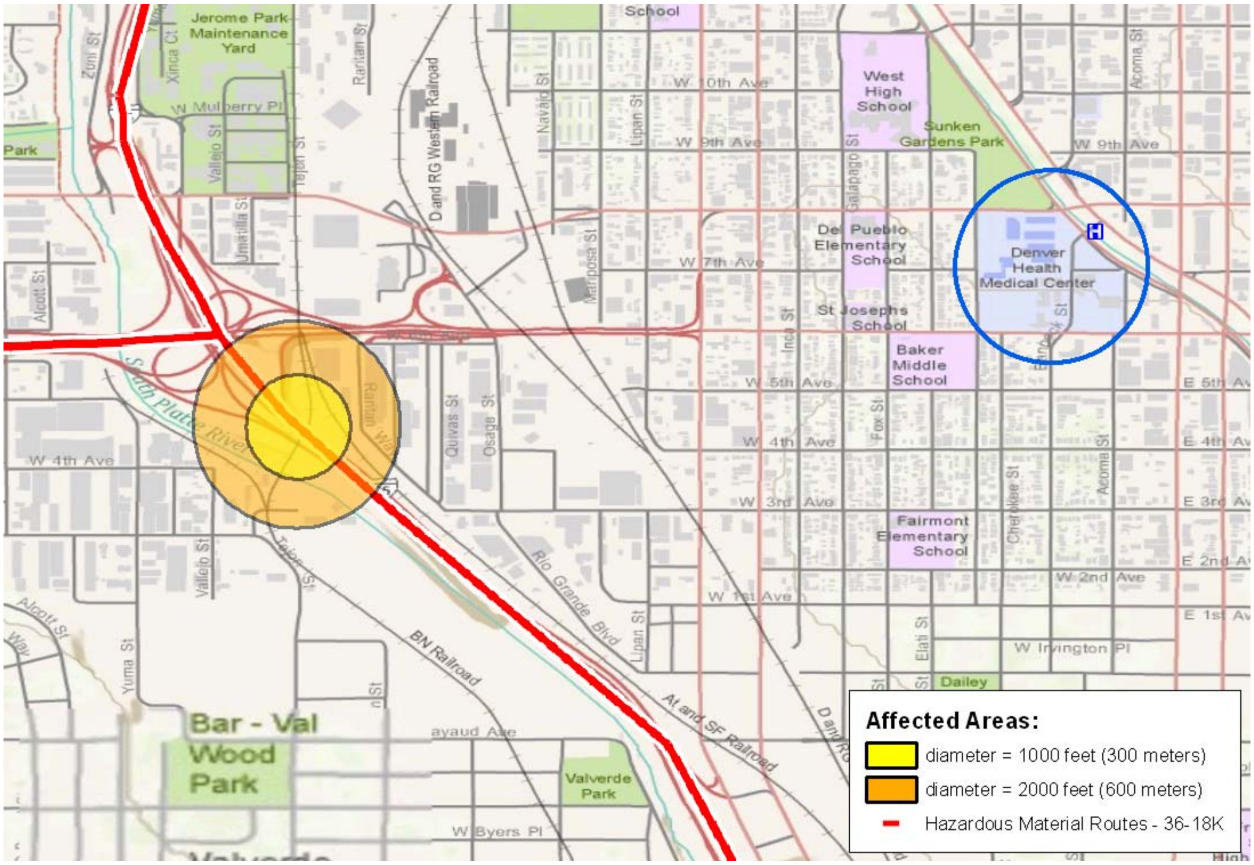


Figure 7.97: Affected area placing a hindrance on the accessibility to the Denver Health Medical Center

Location 5: Proximity to Major Railroads

The final scenario is located where several major railroads are intertwined with the highway system. The functionality of railroads is important in securing the ability to transport goods to and from the Denver Region. The goods could either be exported for profit, or imported to be used by various facilities within the region. If an incident were to occur at this location, three railroad lines would be completely damaged since they are in the 1000 feet affected area (figure 7.98). The three railroads that would be affected area Southern Pacific Transportation, Atchison Topeka and Sante Fe Railroad.

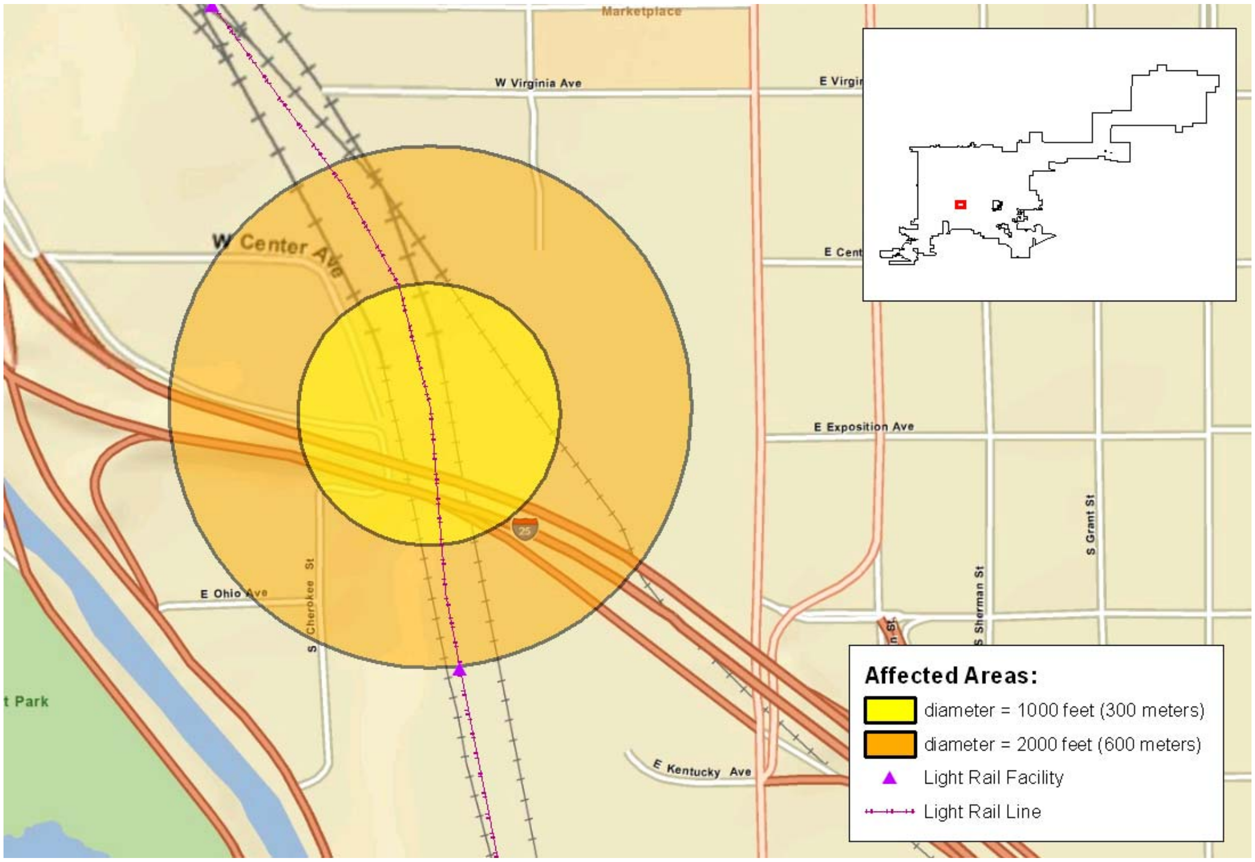


Figure 7.98: Location (5) showing three railroad tracks within the affected area associated with a hazardous material incident

Any transportation of energy products such as coal would not be able to reach their designated destination, possibly affecting the ability for certain factories or energy source facilities from fully operating. These effects could cascade to those felt by the larger community, such as lack of electricity.

To summarize the findings from the five different scenarios presented in this section, it is evident that the transportation of hazardous materials through a major city such as Denver imposes a high level of risk upon its habitants, infrastructure systems, and both critical and non-critical facilities. It is suggested that the designated route be redirected around the city limits away from densely populated areas, and areas where numerous facilities are located. To fully understand all the risks associated with the transportation of hazardous and nuclear materials through Denver, a risk profile should be developed along each of the designated routes, identifying the level of risk along the entire corridors. This risk profile could then be used to promote awareness of the current hazardous situation at hand.

7.4 Flooding

A stressor widely recognized by the Denver Region is flooding. Past flooding events leading to significant damage have become a part of Denver's history, and have not been forgotten. Yet, population growth has attributed to more urbanization amidst FEMA designated 100-year and 500-year flooding zones (FEMA 2010).   Figure 7.99 identifies these flood zones in the Denver Region.

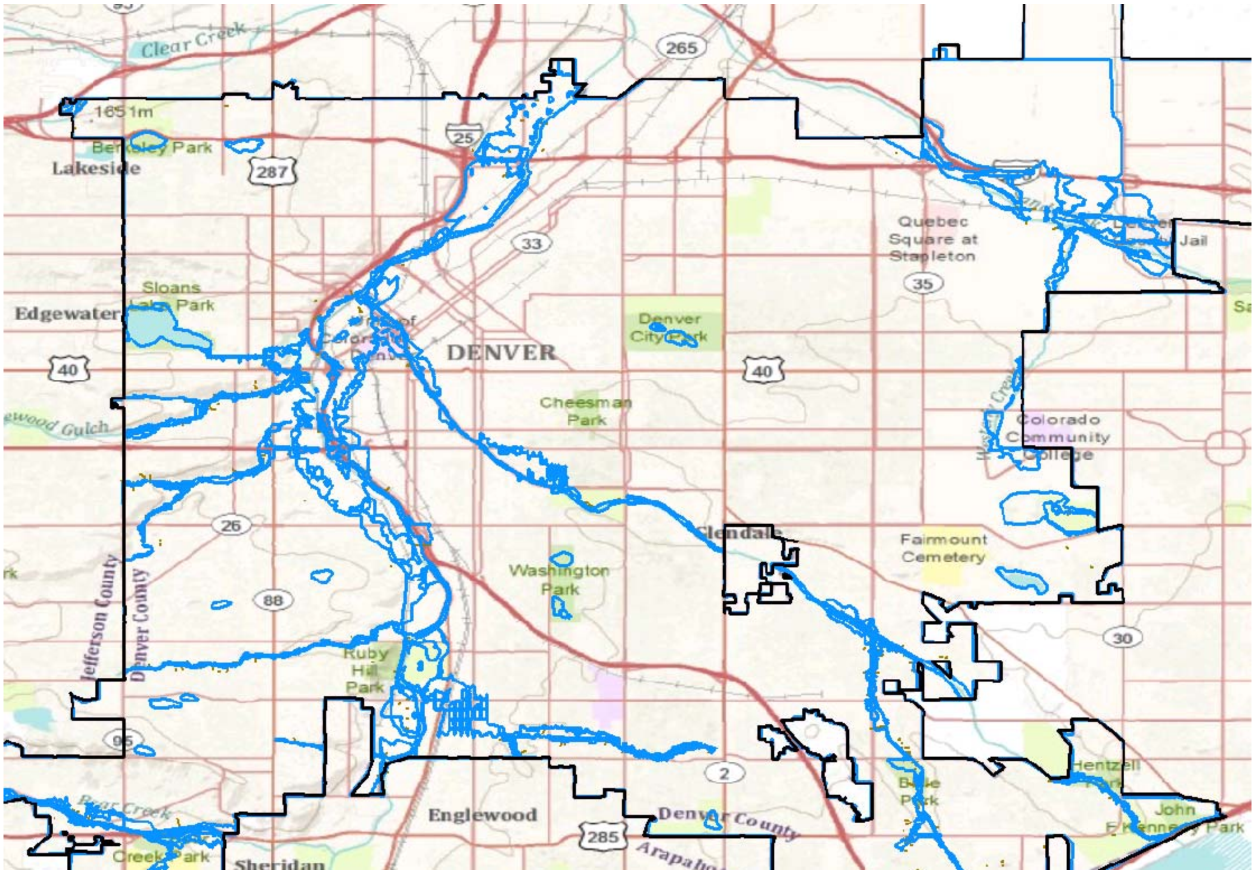


Figure 7.99: FEMA designated flood zones in the Denver Region

Comparing the estimated population growth provided by DRCOG for the Denver Region with the flood zone locations, it is apparent that growth is continuing within several of these hazard zones (figure 7.100). A closer view of these individual locations shows approximately fourteen specific locations within the flood zones where population growth is expected to increase 500-900% by the year 2035 (figure7.101).

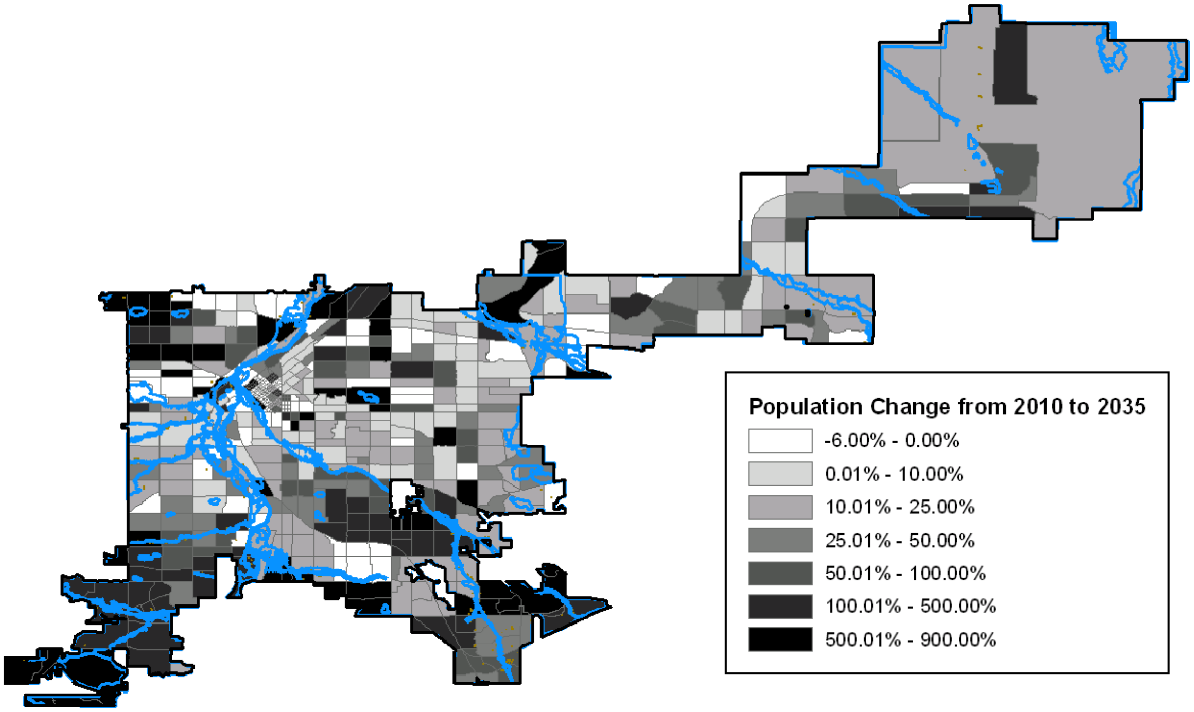


Figure 7.100: Population growth and FEMA flood zones

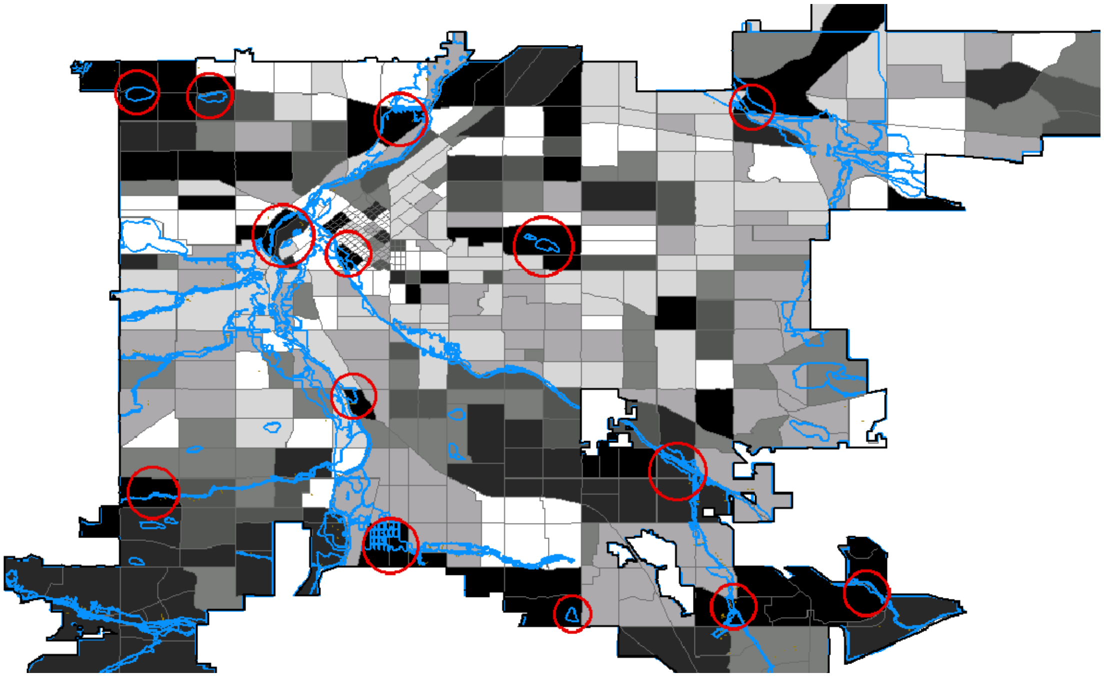


Figure 7.101: Key areas where expected high rates of population growth coincide with FEMA flood zone locations (same scale used in figure 7.100 above)

Furthermore, major transportation routes (including several bridges), key infrastructure facilities, and railways all intersect with these flood zones presenting geographically related vulnerabilities. Continuing to develop in these locations as the Metro Vision 2035 supports will only increase this level of vulnerability. Other areas in the Denver Region will be directly impacted by the proximity of the transportation system to the flood zones in figure 7.102 below since these act as major arteries in the body of the entire Denver Regional transportation system.

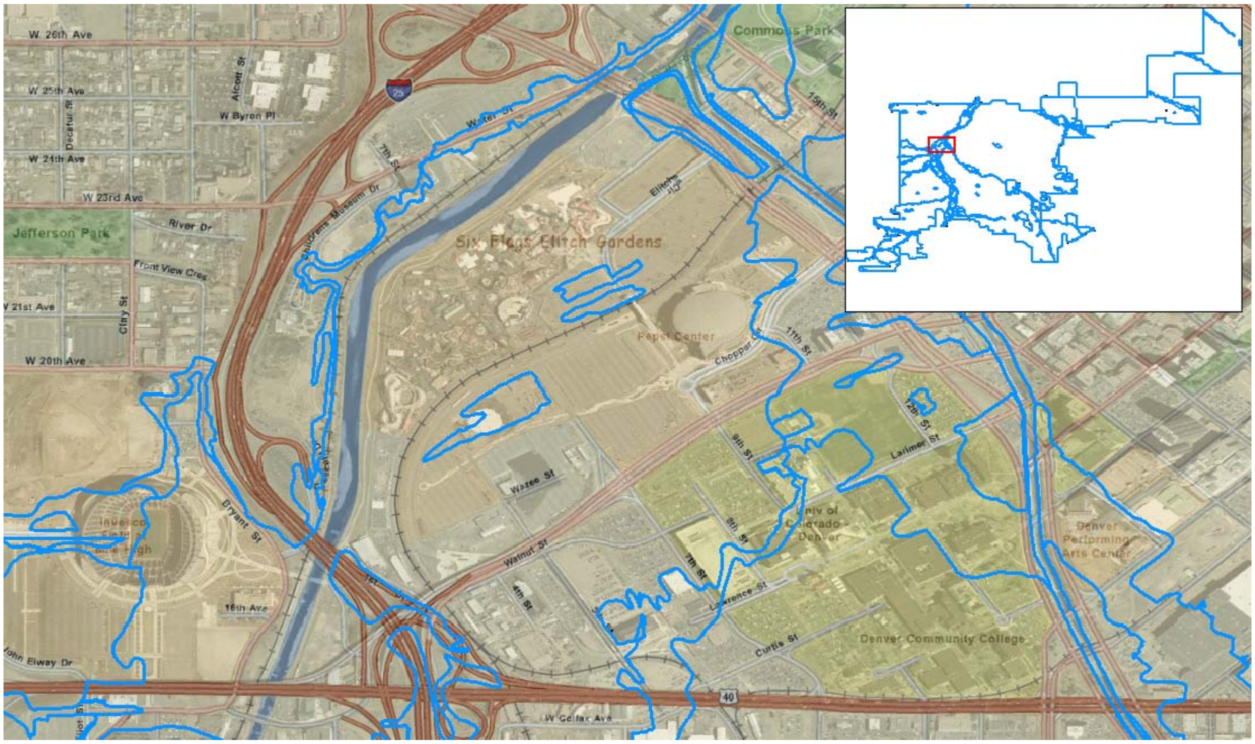


Figure 7.102: Important facilities and infrastructure systems within the designated flood zones

Social vulnerabilities are also exposed to the flooding hazard, demonstrated in the following figures. First, figure 7.103 shows the census tracts with the highest percentage of its population below the poverty level is directly within the flood zones. As mentioned previously, communities already at a social disadvantage prior to the event of a stressor have an increasingly difficult time restoring themselves back to where they were before. Figure 7.104 displays a high percentage of a non-white population in the same location.

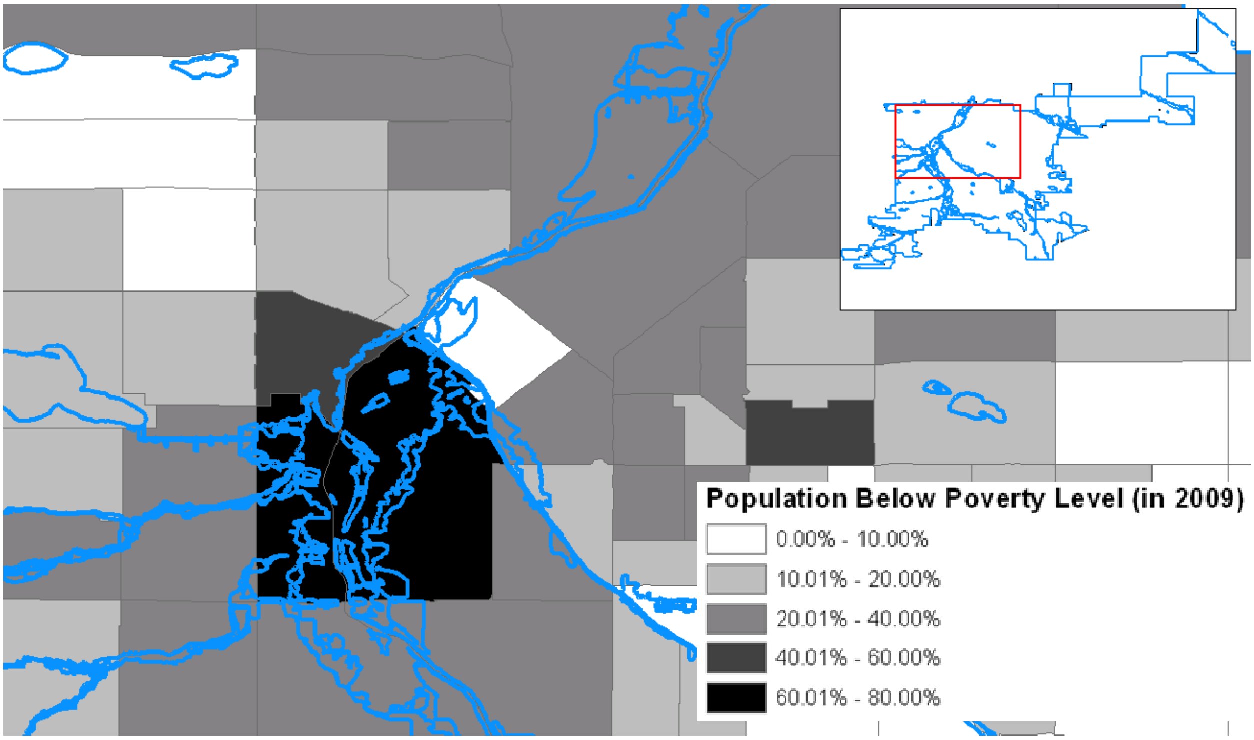


Figure 7.103: FEMA flood zones and percentage of population below the poverty level

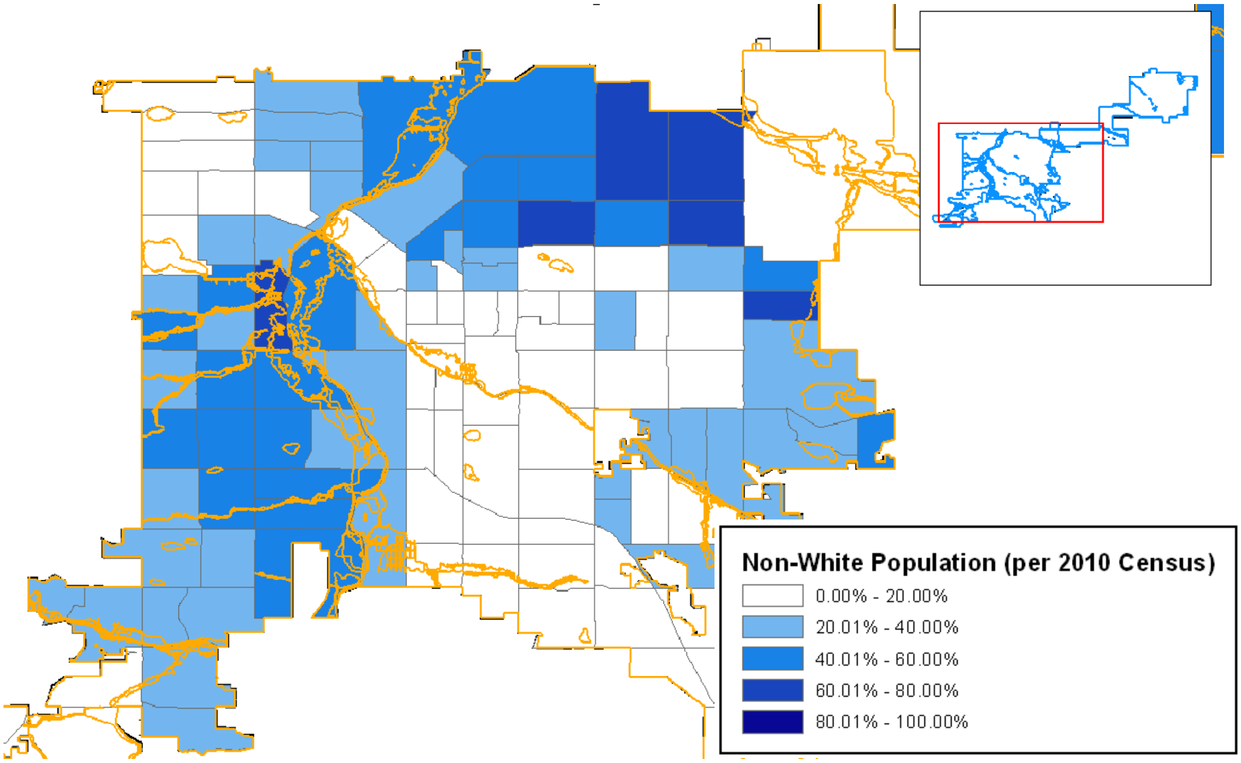


Figure 7.104: FEMA flood zones (outlined in orange) and non-white percentage of the population

The purpose of this section was to re-emphasize the fact that urbanization in the Denver Region is lending toward an increase in vulnerability. City planners need to put forth efforts in mitigating this risk including making a stronger effort of informing the public about the risks associate with developing in a designated flood zone.

7.5 Population Growth

As previously mentioned, Denver has one of the highest population growth rates in the nation. This is an alarming statistic that should be recognized and addressed in order to prevent particular areas susceptible to high population growth rates from being developed in vulnerable locations. Figure 7.105 below shows the percentage increase (and decrease) of population estimated by DRCOG for each census tract by the year 2035.

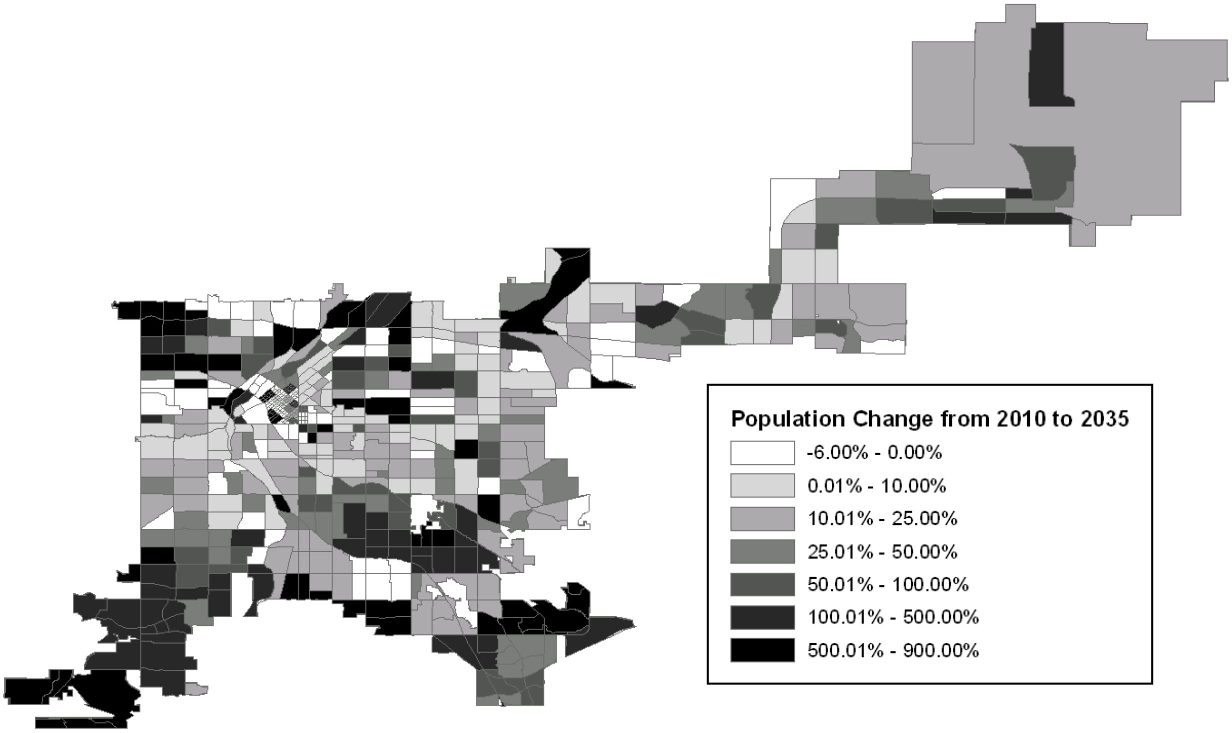


Figure 7.105: Estimated population growth rate across the Denver Region

In figure 7.106 shown below, a side-by-side comparison is made between the 2010 Census population and the estimated population in 2035.

Figure 7.106: 2010 Census population (left) compared to estimated 2035 population (right)

The above figure demonstrates the Metro Vision 2035 (DRCOG 2010) concept of maintaining growth in already urbanized locations. The tracts with high population counts in 2010 continue to grow within the same tract by the year 2035 instead of expanding outward into other tracts. An increase in population density translates into an increase in vulnerability to various stressors. For example, several locations with an anticipated increase in population density per tract by 2035 are directly adjacent to the designated hazardous material routes. Figure 7.107 displays these locations.

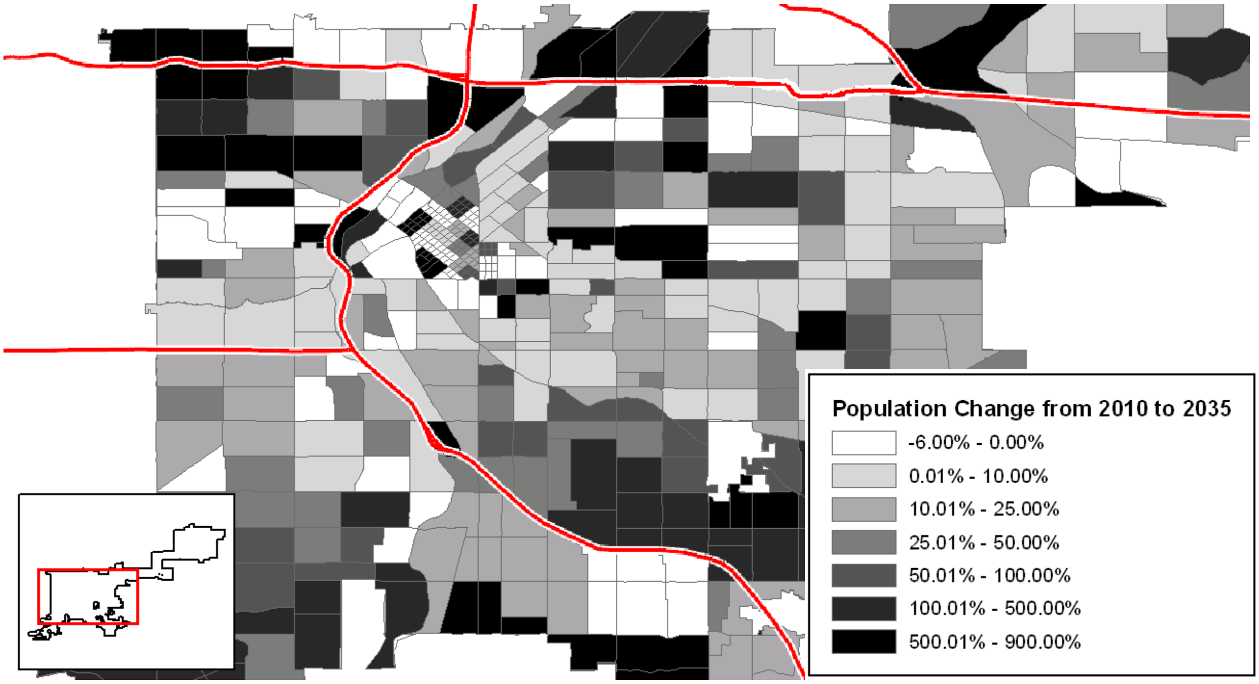


Figure 7.107: Hazardous material routes traversing locations where high population growth is anticipated

Placing the designated hazardous and nuclear material routes through Denver will continue to be a threat to the population and infrastructure systems unless the route is moved to a different location. An investigation of other possible routes, to divert hazardous materials from exposing a risk to the areas is a task that must be performed by the Colorado Department of Transportation.

Chapter 8

Survey on Interagency Coordination

8.1 Survey Background

The development of a resilient and resistant community stems from a strong network of agencies and organizations involved in the planning and the development processes. These groups are from the local, state and federal levels, and require a continuous stream of open communication. Interagency communication is especially critical today as a result of the increasing complexity of infrastructure systems. The advancements in technology and construction capabilities shifted from independent systems into highly interdependent systems as a means of increasing efficiency and reaching larger demands. However, once this heavily integrated system is disrupted by a stressor, the deficiency of one system cascades into the deficiency of another system, and onward.

Proper communication at all levels is the keystone in helping to identify these interdependencies and developing solutions to minimize any possible repercussions. It is the duty of regional planners, emergency management teams, government officials, utility service companies and all other agencies involved in the development of a community to coordinate with one another with the intention of developing plans to mitigate risk. Daniel Alexander, the director of the Office of Emergency Management stated that since he moved to Denver, he was "impressed to see the level of regional integration that had occurred. The state had defined emergency management/homeland security regions, and a coordinator exists within each region to facilitate the development of homeland security strategies, grant funding and information sharing, among other things. Therefore there was a lot of integration in planning and capability building across entire regions" (Holdeman, 2010).

Daniel Alexander's statement sheds a positive light on the coordination being conducted within emergency management teams, but it is important to see if coordination is also being conducted between other agencies involved in city planning operations. To help understand the level of communication between those agencies and organizations in the Denver Region which have an affect on the region's vulnerabilities, a survey was designed to see which ones coordinate with one another and how frequently. Additionally, the survey investigates what percentage of these conversations is guided toward focusing on infrastructure planning that incorporates the potential impacts resulting from various stressors. The full survey can be seen in Appendix B.

The survey was constructed using a free online survey questionnaire tool, *SurveyMonkey*, and distributed to local, state, and federal agencies involved in Denver's infrastructure planning. The following is a list of the organizations and personnel to whom the survey was distributed:

- Federal Emergency Management Agency (FEMA)
- Denver Regional Council of Governments (DRCOG)
- Department of Local Affairs (DOLA)
- North Central All-Hazards Emergency Management Region (NCR)
- Colorado Department of Transportation (CDOT)
- Regional Transportation District (RTD)
- City of Denver's Office of Emergency Management and Homeland Security
- Denver Public Works
- Denver Wastewater
- Colorado Office of Preparedness and Security
- Urban Drainage and Flood Control District
- Denver Health
- Public Health Coordination Center
- Denver Water
- Xcel Energy
- Qwest
- Comcast
- Denver Fire Department
- Mile High Regional Emergency Medical and Trauma Advisor Council (RETAC)
- Colorado Department of Public Health and Environment
- Metropolitan Medical Response System (MMRS)
- University of Colorado at Denver Emergency Preparedness Coordinator

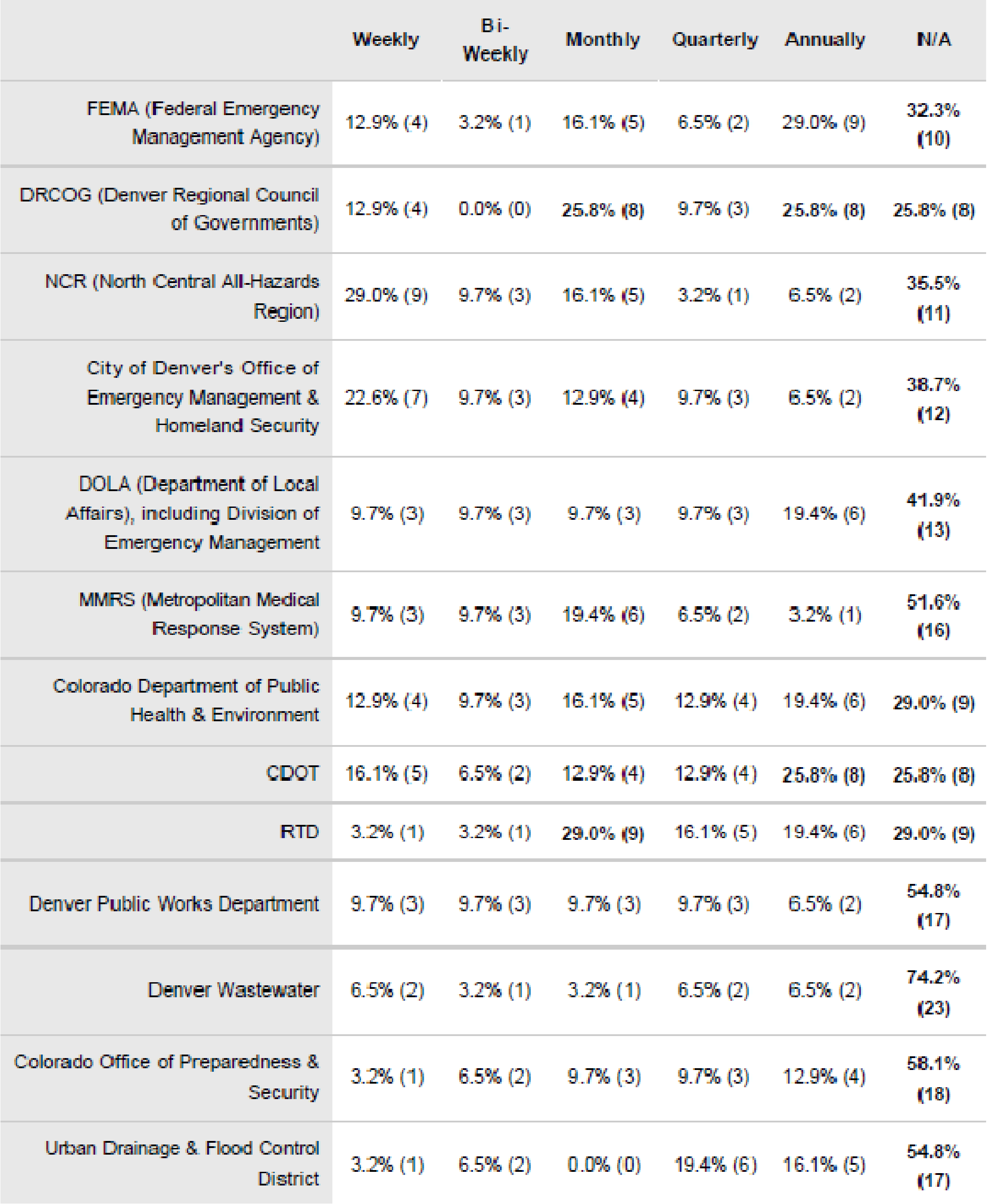
- Pipeline Association for Public Awareness
- Utility Notification Center of Colorado
- Colorado Public Utilities Commission

8.2 Survey Results and Discussion

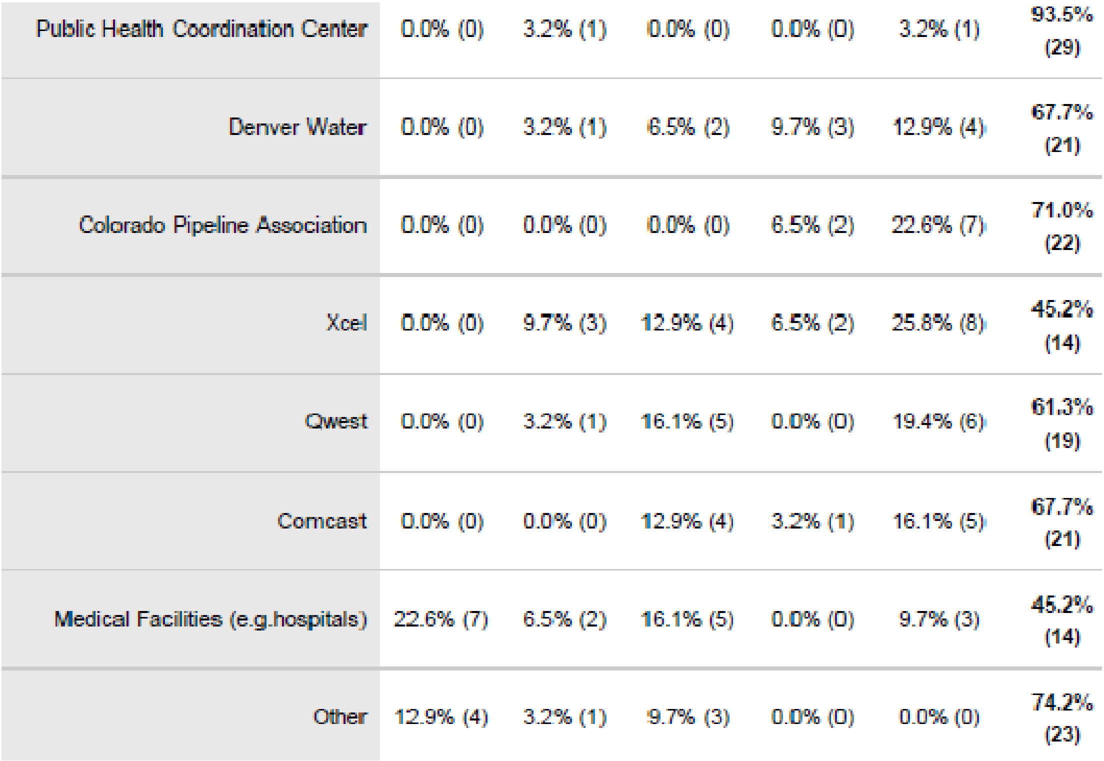
The survey was distributed to an individual representing each of the above organizations, and that person was requested to forward the survey to employees within the organization involved in infrastructure planning and/or mitigation planning, as well as to other agencies/organizations they felt would be candidates for this survey. Unfortunately, the volume of responses was not as high as expected, but there is still valuable information from the data collected. There were a total of thirty-one responses, with a mixture of respondents from the organizations listed above as well as from other organizations to which the survey was forwarded.

Some of the agencies the survey participants work for include: FEMA, CDOT, DRCOG, Denver Public Health, Federal Highway Administration, and South Metro Fire Rescue Authority. A complete list of the participating agencies and position titles is provided in Appendix C. The participant responses are from a wide variety of individuals with position titles such as: traffic operations engineer, homeland security coordinator, GIS analyst, emergency management coordinator, risk analyst, and Director of the Mayor's Office of Emergency Management and Homeland Security. From all the survey participants, 59% work at a local agency, 22% at a state agency, and 19% at a federal agency.

The first question in the survey asked, "What agencies/organizations do you coordinate with, and how frequently do you communicate (e.g., meetings, phone calls, email, etc.)?" The intention of this question was to gain a general understanding of whether or not agencies communicate with several other agencies, and are these conversations frequent or not. Also, to identify particular agencies that are communicated with the most, because these already have strong connections and can be in the forefront in advocating the necessity of agencies working together in building a resilient community. A list of agencies and organizations playing a key role in either emergency response or infrastructure planning was indicated along the left column, and six different response choices were provided for each group indicating how frequently each survey participant communicated to this corresponding agency. The number in parenthesis adjacent to the percentage indicates the number of responses corresponding to the chosen answer. Figure 8.1 shows the survey responses to this question:



	Weekly	Bi-Weekly	Monthly	Quarterly	Annually	N/A
FEMA (Federal Emergency Management Agency)	12.9% (4)	3.2% (1)	16.1% (5)	6.5% (2)	29.0% (9)	32.3% (10)
DRCOG (Denver Regional Council of Governments)	12.9% (4)	0.0% (0)	25.8% (8)	9.7% (3)	25.8% (8)	25.8% (8)
NCR (North Central All-Hazards Region)	29.0% (9)	9.7% (3)	16.1% (5)	3.2% (1)	6.5% (2)	35.5% (11)
City of Denver's Office of Emergency Management & Homeland Security	22.6% (7)	9.7% (3)	12.9% (4)	9.7% (3)	6.5% (2)	38.7% (12)
DOLA (Department of Local Affairs), including Division of Emergency Management	9.7% (3)	9.7% (3)	9.7% (3)	9.7% (3)	19.4% (6)	41.9% (13)
MMRS (Metropolitan Medical Response System)	9.7% (3)	9.7% (3)	19.4% (6)	6.5% (2)	3.2% (1)	51.6% (16)
Colorado Department of Public Health & Environment	12.9% (4)	9.7% (3)	16.1% (5)	12.9% (4)	19.4% (6)	29.0% (9)
CDOT	16.1% (5)	6.5% (2)	12.9% (4)	12.9% (4)	25.8% (8)	25.8% (8)
RTD	3.2% (1)	3.2% (1)	29.0% (9)	16.1% (5)	19.4% (6)	29.0% (9)
Denver Public Works Department	9.7% (3)	9.7% (3)	9.7% (3)	9.7% (3)	6.5% (2)	54.8% (17)
Denver Wastewater	6.5% (2)	3.2% (1)	3.2% (1)	6.5% (2)	6.5% (2)	74.2% (23)
Colorado Office of Preparedness & Security	3.2% (1)	6.5% (2)	9.7% (3)	9.7% (3)	12.9% (4)	58.1% (18)
Urban Drainage & Flood Control District	3.2% (1)	6.5% (2)	0.0% (0)	19.4% (6)	16.1% (5)	54.8% (17)

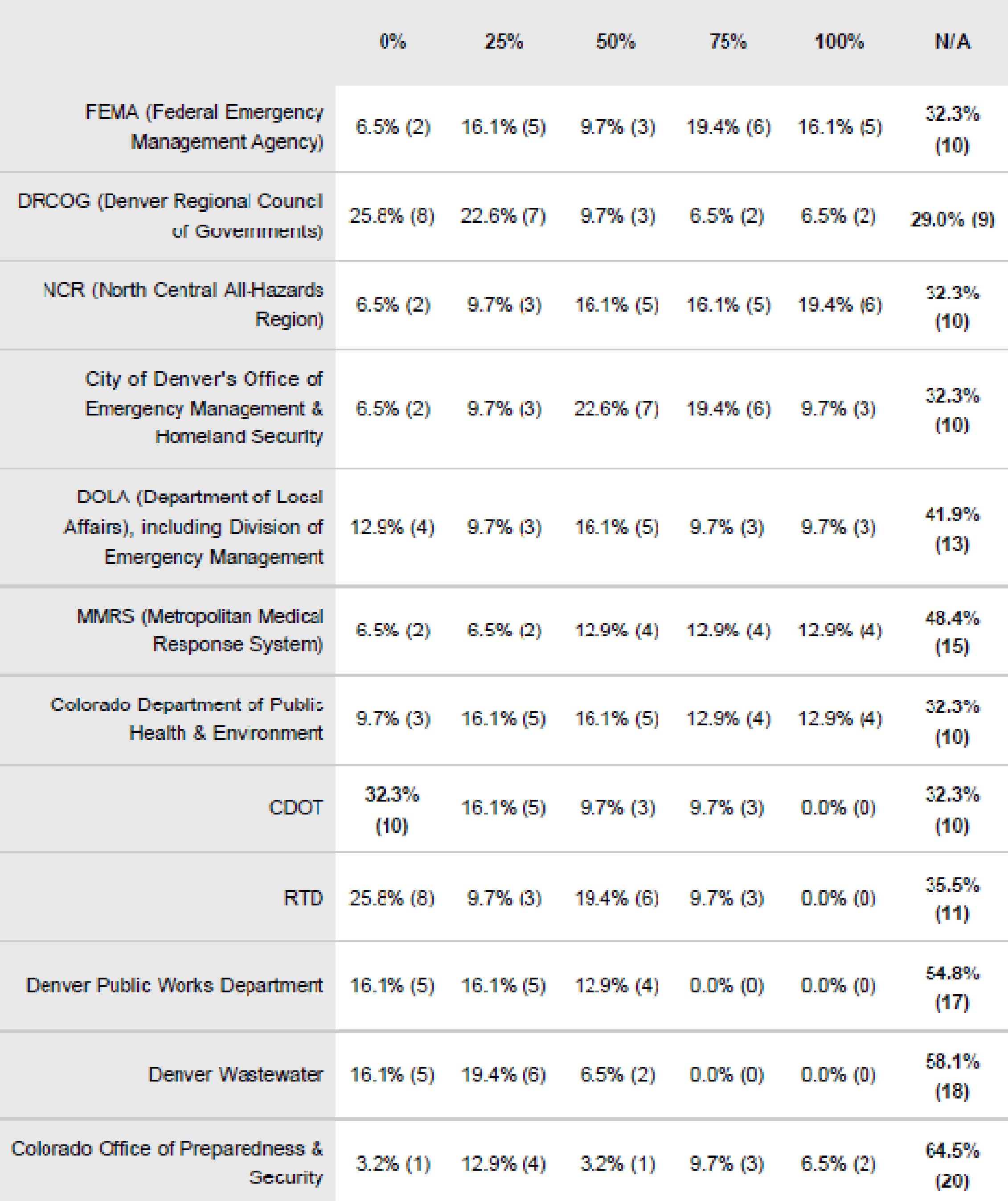


Public Health Coordination Center	0.0% (0)	3.2% (1)	0.0% (0)	0.0% (0)	3.2% (1)	93.5% (29)
Denver Water	0.0% (0)	3.2% (1)	6.5% (2)	9.7% (3)	12.9% (4)	67.7% (21)
Colorado Pipeline Association	0.0% (0)	0.0% (0)	0.0% (0)	6.5% (2)	22.6% (7)	71.0% (22)
Xcel	0.0% (0)	9.7% (3)	12.9% (4)	6.5% (2)	25.8% (8)	45.2% (14)
Qwest	0.0% (0)	3.2% (1)	16.1% (5)	0.0% (0)	19.4% (6)	61.3% (19)
Comcast	0.0% (0)	0.0% (0)	12.9% (4)	3.2% (1)	16.1% (5)	67.7% (21)
Medical Facilities (e.g.hospitals)	22.6% (7)	6.5% (2)	16.1% (5)	0.0% (0)	9.7% (3)	45.2% (14)
Other	12.9% (4)	3.2% (1)	9.7% (3)	0.0% (0)	0.0% (0)	74.2% (23)

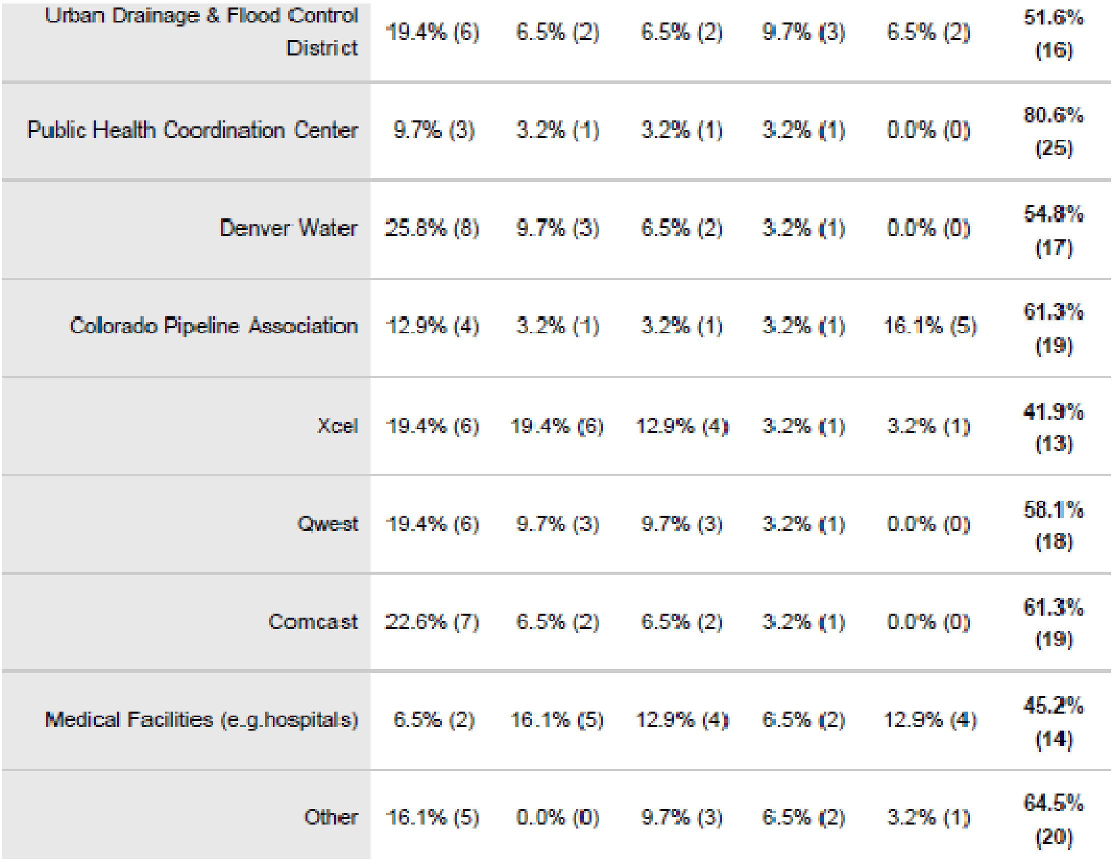
Figure 8.1: Percentages showing coordination between agencies and the frequency of these communications

Based on the responses above, amongst all the agencies specified on the left, only a few of the agencies coordinate on a weekly basis with at least 20% of the responding participants. These agencies are the North Central All-Hazard Region (coordinated with the most on a weekly basis by nine other agencies), the City of Denver's Office of Emergency Management and Homeland Security, and medical facilities such as hospitals. The agencies with the most frequent coordination are the Denver Regional Council of Governments and the Colorado Department of Transportation. Due to the low number of responses to the survey, it is difficult to make definite conclusions as to which agencies are not coordinating with other agencies enough, and vice-versa. The responses do, however indicate which agencies are currently being coordinated with, and provides a basis for a similar study to be performed on a more detailed level.

The second question asked, “In regard to infrastructure planning, approximately what percentage of your conversations with the following agencies/organizations include the potential impact of natural disasters, man-made hazards, and/or intentional attacks?” The responses to this question are shown in figure 8.2.



	0%	25%	50%	75%	100%	N/A
FEMA (Federal Emergency Management Agency)	6.5% (2)	16.1% (5)	9.7% (3)	19.4% (6)	16.1% (5)	32.3% (10)
DRCOG (Denver Regional Council of Governments)	25.8% (8)	22.6% (7)	9.7% (3)	6.5% (2)	6.5% (2)	29.0% (9)
NCR (North Central All-Hazards Region)	6.5% (2)	9.7% (3)	16.1% (5)	16.1% (5)	19.4% (6)	32.3% (10)
City of Denver's Office of Emergency Management & Homeland Security	6.5% (2)	9.7% (3)	22.6% (7)	19.4% (6)	9.7% (3)	32.3% (10)
DOLA (Department of Local Affairs), including Division of Emergency Management	12.9% (4)	9.7% (3)	16.1% (5)	9.7% (3)	9.7% (3)	41.9% (13)
MMRS (Metropolitan Medical Response System)	6.5% (2)	6.5% (2)	12.9% (4)	12.9% (4)	12.9% (4)	48.4% (15)
Colorado Department of Public Health & Environment	9.7% (3)	16.1% (5)	16.1% (5)	12.9% (4)	12.9% (4)	32.3% (10)
CDOT	32.3% (10)	16.1% (5)	9.7% (3)	9.7% (3)	0.0% (0)	32.3% (10)
RTD	25.8% (8)	9.7% (3)	19.4% (6)	9.7% (3)	0.0% (0)	35.5% (11)
Denver Public Works Department	16.1% (5)	16.1% (5)	12.9% (4)	0.0% (0)	0.0% (0)	54.8% (17)
Denver Wastewater	16.1% (5)	19.4% (6)	6.5% (2)	0.0% (0)	0.0% (0)	58.1% (18)
Colorado Office of Preparedness & Security	3.2% (1)	12.9% (4)	3.2% (1)	9.7% (3)	6.5% (2)	64.5% (20)

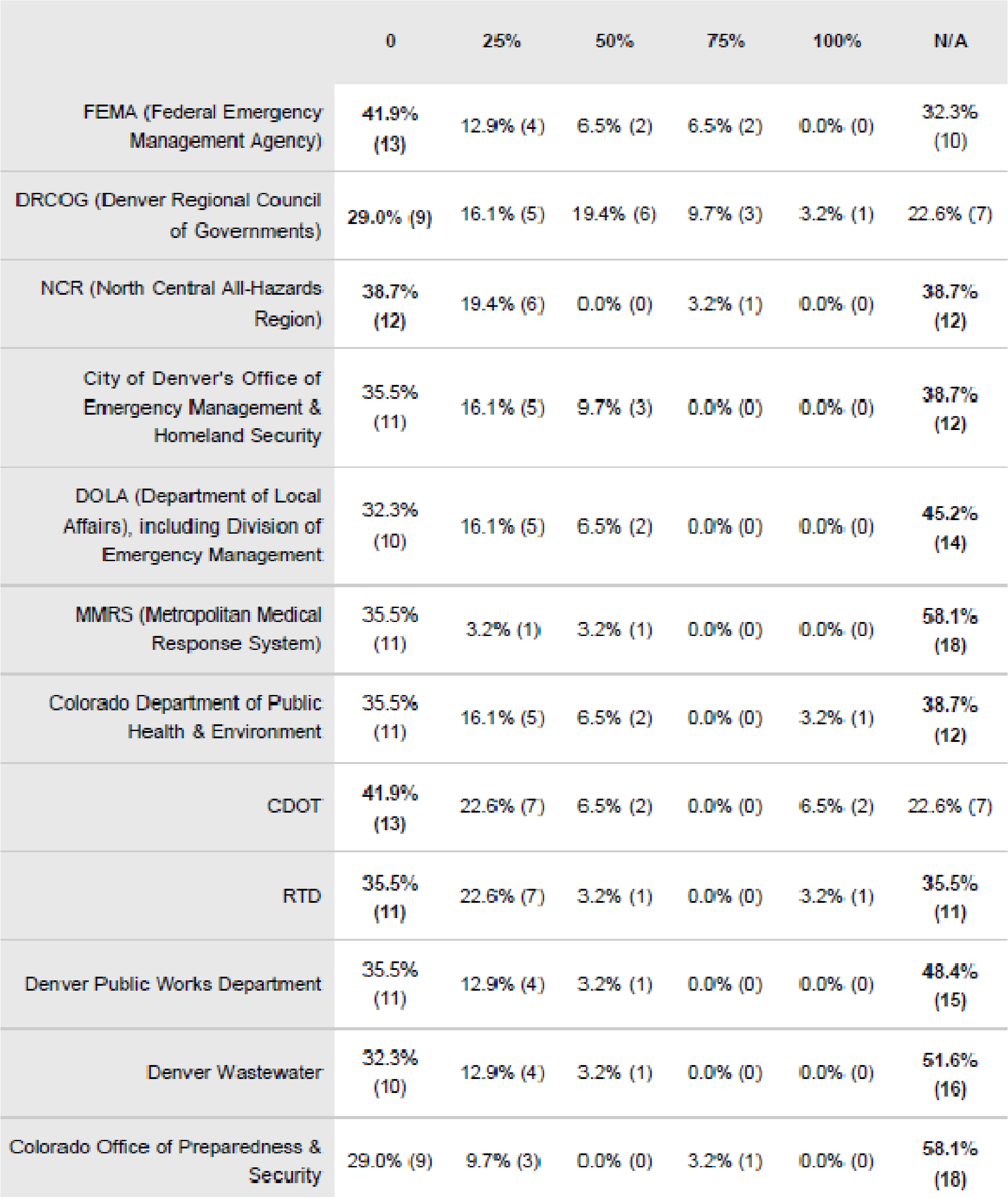


Urban Drainage & Flood Control District	19.4% (6)	6.5% (2)	6.5% (2)	9.7% (3)	6.5% (2)	51.6% (16)
Public Health Coordination Center	9.7% (3)	3.2% (1)	3.2% (1)	3.2% (1)	0.0% (0)	80.6% (25)
Denver Water	25.8% (8)	9.7% (3)	6.5% (2)	3.2% (1)	0.0% (0)	54.8% (17)
Colorado Pipeline Association	12.9% (4)	3.2% (1)	3.2% (1)	3.2% (1)	16.1% (5)	61.3% (19)
Xcel	19.4% (6)	19.4% (6)	12.9% (4)	3.2% (1)	3.2% (1)	41.9% (13)
Qwest	19.4% (6)	9.7% (3)	9.7% (3)	3.2% (1)	0.0% (0)	58.1% (18)
Comcast	22.6% (7)	6.5% (2)	6.5% (2)	3.2% (1)	0.0% (0)	61.3% (19)
Medical Facilities (e.g.hospitals)	6.5% (2)	16.1% (5)	12.9% (4)	6.5% (2)	12.9% (4)	45.2% (14)
Other	16.1% (5)	0.0% (0)	9.7% (3)	6.5% (2)	3.2% (1)	64.5% (20)

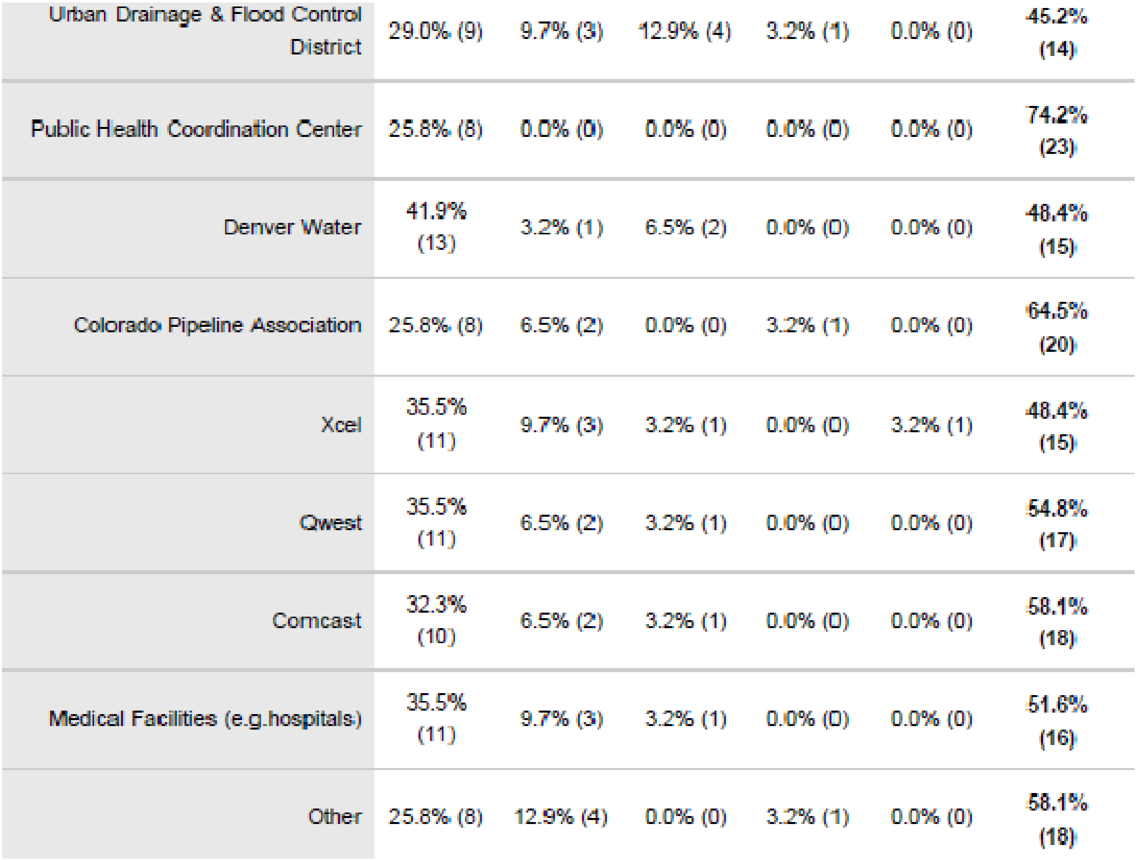
Figure 8.2: Percentage of conversations discussing potential impact of natural disasters, man-made hazards, and/or intentional attacks

The analysis from the survey responses from the second question revealed that several of the agencies listed in the left column do not have discussions related to the potential impact of various stressors with other agencies. For example, the major utility companies, Xcel, Qwest, and Comcast, all show that fewer than 25% of their conversations incorporated topics about natural disasters, man-made hazards, or intentional attacks. In order for proactive measures to be made in building the Denver Region as a more resilient and less vulnerable area, the percentages shown in the response to this question need to be increased.

The third question is identical to the second, but instead of what percentage of their conversations include the potential threat due to natural, man-made, or intentional stressors, this question focuses specifically on population growth. Population growth is often ignored as a stressor because it is not an event that immediately draws attention, but instead is onset more steadily. The percentage of conversations with the listed agencies and organizations concerning stressors associated with population growth are seen in figure 8.3.



	0	25%	50%	75%	100%	N/A
FEMA (Federal Emergency Management Agency)	**41.9% (13)**	12.9% (4)	6.5% (2)	6.5% (2)	0.0% (0)	32.3% (10)
DRCOG (Denver Regional Council of Governments)	**29.0% (9)**	16.1% (5)	19.4% (6)	9.7% (3)	3.2% (1)	22.6% (7)
NCR (North Central All-Hazards Region)	**38.7% (12)**	19.4% (6)	0.0% (0)	3.2% (1)	0.0% (0)	**38.7% (12)**
City of Denver's Office of Emergency Management & Homeland Security	35.5% (11)	16.1% (5)	9.7% (3)	0.0% (0)	0.0% (0)	**38.7% (12)**
DOLA (Department of Local Affairs), including Division of Emergency Management	32.3% (10)	16.1% (5)	6.5% (2)	0.0% (0)	0.0% (0)	**45.2% (14)**
MMRS (Metropolitan Medical Response System)	35.5% (11)	3.2% (1)	3.2% (1)	0.0% (0)	0.0% (0)	**58.1% (18)**
Colorado Department of Public Health & Environment	35.5% (11)	16.1% (5)	6.5% (2)	0.0% (0)	3.2% (1)	**38.7% (12)**
CDOT	**41.9% (13)**	22.6% (7)	6.5% (2)	0.0% (0)	6.5% (2)	22.6% (7)
RTD	**35.5% (11)**	22.6% (7)	3.2% (1)	0.0% (0)	3.2% (1)	**35.5% (11)**
Denver Public Works Department	35.5% (11)	12.9% (4)	3.2% (1)	0.0% (0)	0.0% (0)	**48.4% (15)**
Denver Wastewater	32.3% (10)	12.9% (4)	3.2% (1)	0.0% (0)	0.0% (0)	**51.6% (16)**
Colorado Office of Preparedness & Security	29.0% (9)	9.7% (3)	0.0% (0)	3.2% (1)	0.0% (0)	**58.1% (18)**



Urban Drainage & Flood Control District	29.0% (9)	9.7% (3)	12.9% (4)	3.2% (1)	0.0% (0)	45.2% (14)
Public Health Coordination Center	25.8% (8)	0.0% (0)	0.0% (0)	0.0% (0)	0.0% (0)	74.2% (23)
Denver Water	41.9% (13)	3.2% (1)	6.5% (2)	0.0% (0)	0.0% (0)	48.4% (15)
Colorado Pipeline Association	25.8% (8)	6.5% (2)	0.0% (0)	3.2% (1)	0.0% (0)	64.5% (20)
Xcel	35.5% (11)	9.7% (3)	3.2% (1)	0.0% (0)	3.2% (1)	48.4% (15)
Qwest	35.5% (11)	6.5% (2)	3.2% (1)	0.0% (0)	0.0% (0)	54.8% (17)
Comcast	32.3% (10)	6.5% (2)	3.2% (1)	0.0% (0)	0.0% (0)	58.1% (18)
Medical Facilities (e.g.hospitals)	35.5% (11)	9.7% (3)	3.2% (1)	0.0% (0)	0.0% (0)	51.6% (16)
Other	25.8% (8)	12.9% (4)	0.0% (0)	3.2% (1)	0.0% (0)	58.1% (18)

Figure 8.3: Percentage of conversations directed on population growth

The responses seen in figure 8.3 above clearly indicated that population growth is not a primary topic. For the agencies that do communicate about population growth, the percentage of their conversations focused on this topic is approximately 25%. It is interesting that the responses for the utility companies in particular show that population growth is not a major topic, yet population growth would have a direct impact on their demand. Since the Denver Region is one of the fastest growing regions in the nation, the effect of population growth should not be underestimated.

The final survey question asks the participant to indicate on a scale from 1 to 10 how vulnerable (in terms of man-made or natural hazards) do they think the following Denver Region systems are: transportation, water, wastewater, electrical/power, communication, and emergency response. Figure8.4

graphically shows the responses, with the color coded legend on the right-hand side indicating the perceived level of vulnerability (with 10 being the most vulnerable).

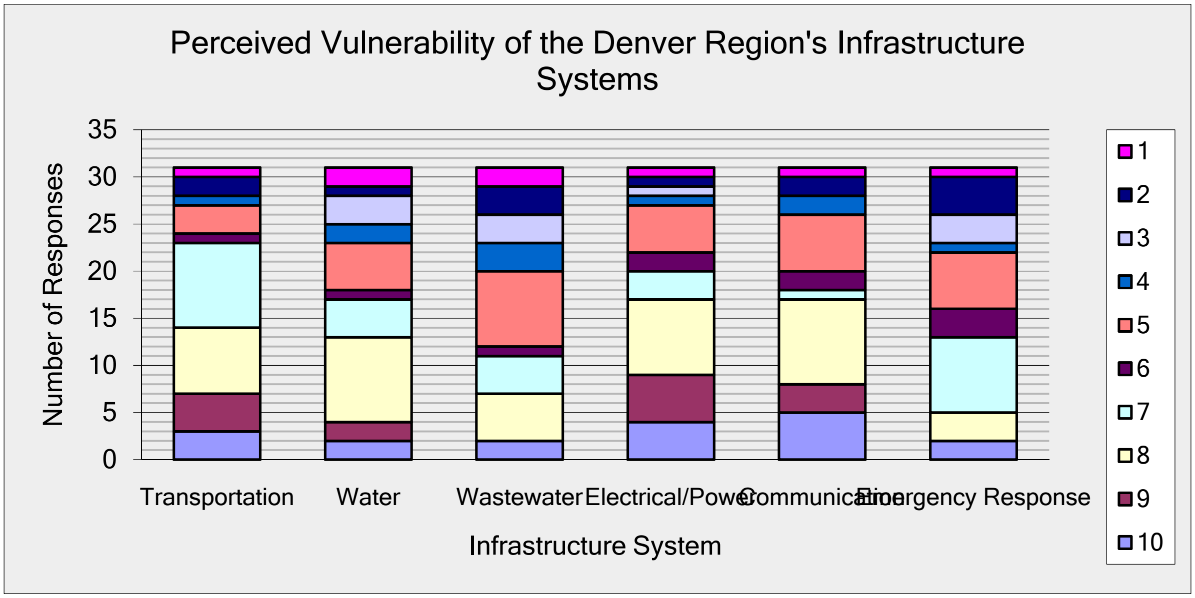


Figure 8.4: Perceived vulnerability rankings for infrastructure systems in the Denver Region (10 being the most vulnerable)

From the thirty-one responses collected for this question, there is no clear indication as to which infrastructure system is seen as the most vulnerable. It appears that each respondent has a different perception, with responses ranging from a vulnerability level of 1 to a level of 10 for the same infrastructure system. The responses to this question reveal both that each of the six infrastructure systems are viewed as vulnerable by at least a few of the participants, and that perhaps the awareness of the vulnerabilities existing in the other systems is unknown to some but known to others, showing a disconnect in the communication between these different agencies. Vulnerability is also a difficult concept to quantify; therefore each individual may have a different understanding of the various levels of vulnerability.

Chapter 9

Interviews

9.1 Discussions with Denver Regional Agencies Key Personnel

Interviews were conducted with nine key personnel in several Denver regional agencies in an effort to gain an understanding of the different strategies currently being used to mitigate risk associated with infrastructure planning, including topics on hazards mitigation and emergency preparedness. The interviews were not formal but conducted more in a discussion type format, allowing each of the participants from the chosen agencies to provide specific information about their agency's role in promoting a more resilient infrastructure system in the Denver Region. The agencies participating in these individual discussions as well as the positions of the participants are included in Table 9.1 below:

Table 9.1: List of organizations and positions of participants interviewed:

Organization:	**Position(s):**
Denver Regional Council of Governments (DRCOG)	-Geospatial Team Manager -Regional Modeling Manager -Socio-economic Analyst -MPO Planning Program Manager -Regional Planner
Federal Emergency Management Agency (FEMA)	FEMA Region VIII Mitigation Division: -Risk Analyst/GIS Coordinator -Senior Physical Scientist
Office of Emergency Management and Homeland Security (OEM)	-Emergency Management Coordinator Planning Specialist and TIER II Contact
North Central All-Hazards Region	-NCR Homeland Security Infrastructure Protection Analyst

Through the discussions conducted with the individuals listed above in Table 9.1, several key findings were made. First, data collection and analysis has proven to become a difficult task, however strong efforts are continuing to be made in order to solve this problem. Second, natural hazard analysis for the Denver Region has been solely focused on flooding. Earthquake hazard has been identified but not addressed in infrastructure planning decisions. Third, there continues to be a disconnect among local agencies and organizations, preventing issues involving system interdependencies from being addressed. Each of these topics amongst others will be discussed in further detail throughout this section.

One of the main components in successful infrastructure planning is having sufficient data for the region to develop accurate models depicting overall infrastructure performance. This performance is affected by demographics, population growth, building types, hazards, etc. The level of detail of the data required as input into models used to understand the performance of the infrastructure system is extensive, and the results of a model are only as accurate as the data inputted into the model. Along with data collection and level of detail, another issue is the ability to combine the results from various models. For example, there are models used for transportation planning (including roadways and transit), ones used for land-use planning, and models used for hazards simulations, however there is not one model combining all these capabilities. The infrastructure system is highly interdependent, a concept not demonstrated in these models. It is very complicated to develop a model that has the ability to take into account all the different variables, thus each model remains independent of the other. With the advancements in technology allowing for more detailed data collection and storage, progressive movements are being made to eventually allow for models to accurately incorporate the system interdependencies. Currently, some of the regional models are focused on travel mode and land use models.

The advancements in collecting vast amounts of detailed data have become a key factor for planning decisions made today. The Denver Regional Council of Governments (DRCOG) is in the forefront in collecting data and “massaging” the data for use at the regional level (DRCOG 2010). Through several discussions with DRCOG, issues involving data collection and data use were identified. For instance, some of the data that is in currently missing is detailed building and employment inventory data. Both of these are important for land-use modeling as well as hazards modeling. DRCOG has been working for several months in 2010 and 2011 in obtaining these data. The data should be completed in the near future in 2011 and used for more accurate land-use modeling (DRCOG 2010). These data would be valuable as input into programs including HAZUS to obtain more accurate and detailed results. Efforts currently being made to obtain these data will help resolve some of the issues in regard to lack of building information and employment data used in various infrastructure models. Even the Federal Emergency Management Agency (FEMA) has difficulty obtaining private sector data because it is not readily available, again affecting certain analysis (FEMA 2010).

Another issue presented by DRCOG is the difficulty in collecting various data. For instance, power supply companies previously provided DRCOG with detailed household data. However, due to underlying issues, power supply companies discontinued providing these data. There are several of these instances where some surrounding local governments refrain from sharing data with DRCOG simply because they either want more money for their data or for other unknown reasons. The mentality to withhold data information from different agencies or local governments for no strongly justified reason is part of the culprit in the issues stemming from the lack of data, ultimately preventing necessary analysis from being conducted.

Data collection on critical infrastructure and facilities is another challenge. Since security levels have been heightened in recent years, it is difficult to obtain any data related to critical structures. Xcel energy will not share any information even to the North Central All-Hazards Region (NCR), which looks at high risk areas. In addition, DRCOG was unable to attain critical facilities data from the North Central All-Hazard Region (NCR) strictly due to security reasons (DRCOG 2010). FEMA also has data which they are not allowed to share, in particular data from the Department of Homeland Security (FEMA 2010). Although there is logical reasoning behind not providing this information, there are reasons why this information should be shared with agencies involved in city planning. DRCOG simulates models that take a close look at where the transportation system should be developed or modified. These models exclude information in regard to the proximities of these critical facilities to the transportation system. As seen in chapter 7, the transportation of hazardous materials along major highways in Denver poses a threat to several critical facilities adjacent to these highways. Coordination needs to be performed to prevent similar risk.

There are several examples demonstrating the lack of data sharing, including alert system locations. FEMA does not have specific information identifying the locations of alert systems in the region, whereas DRCOG has some of this information. In addition, Qwest, along with other communication providers, have more confidential information that is shared between them, but not distributed to planners including DRCOG (FEMA 2010). The lack of data sharing builds a wall between different agencies and organizations that need to coordinate with each other more due to the complexity of the infrastructure system and the interdependencies that currently appear efficient, but will result in more damage and catastrophe in the event of a disaster.

Transportation modeling has been a progressive process over the years. Attempting to understand patterns within the transportation is a significant challenge. The number of independent variables identifying people's behaviors associated with the transportation system is infinite. DRCOG has developed a regional travel model guided toward being an effective tool used in making informed policy decisions that affect the quality of life of the population in Denver Region. The two main questions asked by policy decision makers that are to be addressed by this model are, "how to spend our limited money on building and maintaining roads and transit" and, "where to plan for future land development for housing and businesses" (DRCOG 2011). With Denver's rapidly increasing population, traffic congestion will follow. The travel model used to help manage this issue is called the Focus model. Focus analyzes the transportation system at a detailed level by simulating the probable behaviors of each individual. Several factors that affect everyday travel decisions include age, income, whether or not they have kids, amongst many others. The data used by this model were collected using a survey (the household travel diary summary) to develop statistical models of people's choice behaviors; where they will go, the purpose of their travel, how often the travel, what method do they use to travel, etc. The survey included a sample population of 7,200 households representing a random sample population. From the survey's responses, utility functions were developed based on observed behaviors from the survey, showing what are the factors that influence people to make the choices they make. For example, households with more elderly people tend to make fewer trips (DRCOG 2010).

Using these utility functions, desirability scores were assigned to each of the choices faced by the person traveling. From these scores, the model assigns a probability to each of the choices. In the case of the probability of the mode of travel chosen, factors are included in this decision based on the previous choices made by the individual, as well as factors including the estimated time of travel or whether or not there are parking charges where their destination is located. Each of these factors is used to determine a score that assigns a probability as to which mode of transportation they will likely use (e.g., they are 75% likely to drive from point A to point B). This model can be used as an effective tool in analyzing future scenarios associated with the predicted urban growth in the Denver Region (DRCOG 2010)

Transportation modeling programs, such as Focus, are primarily intended to be used for decisions such as proposals for new transit lines. The decision makers need to estimate the number of passengers and ultimately the potential revenue from the new lines. Unfortunately, funding determines the primary use for transportation models, which is to help developers make economical decisions. At DRCOG, hazard analysis is not incorporated in transportation planning. The link between hazards analysis and how it affects planning is missing. Instead, it is assumed that more site-specific analysis will be conducted and addressed by engineering solutions (DRCOG 2010). Instead, transportation models should also be used to understand the interdependencies with other infrastructure systems and in hazards planning. Typically, only flooding is considered as a main hazard in the region, yet if a major event such as an earthquake along the Golden Fault line were to occur, large segments of the transportation system would be affected. The location of major highways and transit systems are not determined by engineering solutions but instead by city planners. Modeling human behavior in relation to the transportation system and determining solutions that address revenue, human safety and infrastructure interdependencies is a more optimal solution that considers future events (population growth, natural disasters, and man-made hazards).

DRCOG has several policies that define the overall goals of the organization. Policy #10 specifically addresses interconnections in the Denver Region, with the idea of providing “efficient interconnections of the transportation system within modes, among different modes, and between the metropolitan area and the rest of the state and nation” (DRCOG 2010). Some of the key action strategies listed in policy #10 that would need to be looked at individually in conjunction with hazard analysis include:

- Improve transportation linkages to major destinations and attractions outside the region
- Facilitate the movement of goods throughout the region by reducing obstructions such as congestion, bottlenecks, and disconnections between facilities, while providing sufficient opportunities for intermodal freight connection.
- Develop the Denver Union Station to function as the primary multimodal hub of the regional transportation system. Consider the development of rapid transit hubs in all major communities.
- Consider opportunities for the development of an intercity commuter rail or bus system along the Front Range, and also incorporate, within the region, elements of statewide intercity rail system.
- Ensure convenient access to Denver International Airport (DIA) for all modes of travel, and maintain DIA’s important role in connecting the Denver region to the rest of the nation
- Support continuing activities that might eventually enable through rail freight traffic to bypass population centers

  (DRCOG 2010)

The acknowledgment of the importance of interconnections within the transportation shows that the issues are there and need to be addressed. However, these action strategies only recognize interconnections amongst the transportation system and not amongst other infrastructure systems including water, electricity and communications. Action strategies involving the interconnections between all systems need to be conducted.

From discussions with Federal Emergency Management Agency (FEMA 2010), they also recognize this disconnect. It would be more meaningful if mitigation was coordinated with development and capital planning (FEMA 2010). Building each element of the infrastructure system correctly the first time, recognizing future growth along with risk, would be optimal, but not successfully doing this has been a major weakness in the planning process. One positive improvement in the planning process is that resources are now being pushed to more at risk areas instead of equally distributing the resources. Equal distribution spreads the resources too thin, not providing areas that need the resources the adequate amount needed.

Each agency and organization has a specific role in the Denver Region. DRCOG's primary focus is the transportation system, whereas FEMA takes the role of looking at the social needs within the community. For example, FEMA is more concerned with the protection of shelters, schools, hospitals, etc. Each of these agencies looks at population growth as a stressor. DRCOG considers population growth when determining the capacity of the transportation system and traffic congestion. Observing the population growth is important to FEMA to estimate the number of shelters that would be required if a certain disastrous event were to occur. Also, FEMA can locate densely populated areas and associate a level of vulnerability to those locations. Each state has its own culture, and FEMA recognizes this. For comparison, if Salt Lake City were to experience an earthquake, the population would be much more resilient in responding to the hazardous event than if Denver were to experience the same earthquake. The reasoning behind this statement is that the residences of Salt Lake City have a message of preparedness that everyone follows. A survey was conducted in Salt Lake City showing about 70% have an emergency kit assembled and ready to use. Part of this statistic is strongly related to the religious beliefs of many who live in the area. If the same survey were conducted in the Denver Region, the percentage of people who have an emergency kit ready would likely be much less. One of the issues is that the risk of an earthquake event or other hazard has not been advertised to the Denver Region, allowing the population to ignore the possibility of such an event occurring. Another example is if the same intensity of a severe snow storm were to occur in Denver as well as in Georgia, Denver would be more resilient. When a region is use to a hazard, it adapts and allows it to become more resilient and resistant to the same event in the future (FEMA 2010).

Another key organization involved in the sustainability of the Denver Region is the North Central All-Hazards Region. Its vision is to “improve region-wide emergency preparedness, response and homeland security capabilities through collaborative and inclusive planning and resourcing efforts” (NCR 2010). Improving inter-jurisdictional communication and coordination is one of the many goals of NCR. The survey results shown in chapter 8 verify NCR is successfully promoting coordination, with the highest percentage for organization communicated with on a weekly basis. NCR is an organization that understands the criticality in maintaining frequent communication.

Discussion with an NCR Homeland Security Infrastructure Analyst provided an understanding on how risk is measured and the importance of presenting the risks associated with the Denver Region to the stakeholders. First, the value of risk is calculated as the product of assets, vulnerability, threat and consequence. The assets/resources variable is the percentage of the total county reported assets. The other values are assigned a relative value from predefined scales provided by the Department of Homeland Security or Colorado Department of Public Safety. Examples of assets include state and federal buildings, courts, military installations, water treatment, distribution centers, emergency operations centers, schools, substations, refineries, airports, transit stations, bridges, and dams. Because it is impossible to protect every asset and person against all potential threats, there must be a way to assign priorities for which the resources are allocated, and this is done by calculating the value of risk (NCR 2010).

As part of the North Central All-Hazards Region, the Colorado North Central Region's Critical Infrastructure Protection Committee conducts several meetings annually. These meetings are intended to be valuable to the private sector members. An example of a topic discussed at one of these meetings (October 28, 2011) is the effect of an earthquake on regional critical infrastructure sectors and the interdependency problem for locations outside of the affected area. They want to develop a product displaying a model showing these effects and interdependency issues to present at a future Critical Infrastructure conference. Using a model earthquake, some of the potential effects would include 911 calls being backlogged, petroleum and natural gas pipelines being severed (affecting ones that run from Colorado to Wyoming and Texas), a large segment of Denver being dark since much of the energy distribution would come from the affected area of the earthquake, and Denver International Airport not having jet fuel because the Suncor Oil Refinery would no longer be operating. Other issues resulting from the model earthquake include: several hospitals would be damaged, and Qwest and Gateway would have a cascading effect because their main data processing centers are in the affected area (NCR 2010). The purpose of this particular meeting was to help gain the attention from different sectors to add more information to the maps showing the affects from the earthquake. By showing various sectors how an earthquake event will affect them, the more likely it is that actions will be taken to mitigate the potential amount of damage.

One of the points brought up at this meeting was that long-term recovery must be considered. For example, the 1960 Chatfield flood event in Denver took 3-4 years to fully recover. An earthquake would take much longer for Denver to recover (NCR 2010). However, when speaking to FEMA, long-term recovery plans are rare to compile in advance. Instead, each recovery plan depends on the local communities. The local communities need help because they are not as strong once they have been impacted by a disastrous event, and therefore they require outside assistance. As noted, however, the long-term recovery plan is generally set in place after an event (FEMA 2010). This again shows there is a disconnect in ideas between various agencies.

The second main focus of this NCR meeting was to share the news that Colorado has received grants to develop Energy Assurance Plans that will link Public Emergency Operations Plans with the Energy Sectors Emergency Response Plans and the public and private sector energy needs of the community during an energy outage. In the summer 2010, an outage occurred as a result of a transformer explosion, causing several citizens and sectors to have problems, emphasizing the need for the grants mentioned (NCR 2010). This is an example of some of the efforts being conducted that will help the Denver Region become more sustainable and resilient.

The Office of Emergency Management and Homeland Security (OEM) is another key agency greatly involved in mitigation efforts in Denver. The mission of the Mayor's Office of Emergency Management and Homeland Security is "to effectively collaborate with our stakeholders to increase the City's and the region's all-hazard protection, preparation, mitigation, response, and recovery capabilities" (Alexander 2010). The OEM provides resource management, sheltering and evacuation plans, and other services critical in the event of an emergency. The Denver Emergency Operations Center is also located within the OEM office in downtown Denver. This center allows for fire services, law enforcement, public works, mass care, communications, public health, environmental health, airport, and private sector personnel to congregate in the same room after a disastrous event has occurred. There is one person for each of the operation sectors listed above who comes to this center at the time of an emergency. This allows for all sectors to be present to allow for efficient and centralized communication and operations (OEM 2010). Having each of these sectors come together shows how interdependent the sectors are viewed. The coordination conducted in the center is the type of coordination that should be done prior to a hazard to help mitigate hazard effects.

Open discussion with the management coordinator and planning specialist helped gain a perspective of the status of the Denver Region's recovery plan. Initially DRCOG wrote the OEM's hazards mitigation plan. The original plan was submitted to FEMA, and then sent back for revisions, including adding a significant amount of more detail. DRCOG found frustrations in meeting FEMA's requirements and no longer writes the OEM's hazard mitigation plan. Currently, the Federal government has chosen Denver as one of a few locations where they will construct the recovery plan. The writing of the new plan has begun in January 2011 (OEM 2010). Once the plan is provided, it will be interesting to see what types of hazards it considers as the main threats to the Denver Region.

Some additional points found through these discussions include that hazards planning is reflected in the infrastructure system through the city dealing with zoning codes (OEM 2010). Again, these zoning codes stem from the land-use models provided by DRCOG, showing the interconnection between these agencies. However, social vulnerability has not been considered in Denver by the OEM at a detailed level. This is one of the current problems that is being addressed. Such studies will help develop the zoning codes for the Denver Region to help mitigation efforts. Another interesting point that was found in this discussion is that the OEM currently does not have pipeline data. Pipelines are a critical component in the infrastructure because they are highly interdependent with the other systems. For the Office of Emergency Management to not have pipeline data shows there is much room for improvement. The personnel currently working in the OEM are making strong and effective efforts to obtain such data and to develop a strong mitigation plan, which was previously lacking. It was not until the Democratic National Convention in 2008, that security was truly considered in a coordinated fashion in the Denver Region. Mitigation planning is a long process that is currently being conducted to help Denver become more resilient.

Through conducting discussions with several key personnel in Denver regional agencies, an understanding of the individual roles of each agency was identified. In addition, some of the current issues preventing Denver from becoming a more resilient county were presented. The primary issues include: missing data, lack of data sharing, and lack of addressing issues of interdependencies amongst Denver's Infrastructure. The hope is that efforts in the near future will be geared toward more interagency coordination to address these issues in regard to interdependencies.

Chapter 10

Conclusion

10.1 Remarks

Infrastructure systems today have reached an alarming level of complexity as a byproduct of the interdependencies linking one system to another. Water, electrical, transportation, and communications systems all depend heavily upon one another creating an intimate network which requires advanced methodologies and techniques to help identify the network's nodes of interconnectedness hidden to the human eye. Through case studies examining past disastrous events the cascading effect of infrastructure system failures can be explored to help prevent similar situations from repeating. However, solely looking at case studies to identify all the underlying interdependencies for a specific study region is an incomplete approach. Instead, individual analysis using tools such as geographic information systems should be utilized to examine a study region based on that area's unique characteristics (geographically and socially).

In this thesis, several conclusions can be made from examining the risks and vulnerabilities within the Denver Region that should not be ignored in future development and mitigation planning. First, disregarding an earthquake hazard in the Denver Region poses as a potentially detrimental mistake. Until more recently, seismic behavior in Colorado has basically been ignored, yet the event of an earthquake could result in one of the most disastrous events seen in the history of Denver. The results from the two earthquake scenarios, (the Rocky Mountain Arsenal Fault and the Golden Fault), show hundreds of possible casualties and billions of dollars in economic losses estimated using HAZUS. Figures created in ArcGIS displaying the locations and magnitudes of losses within the region can be used as a platform in bringing an awareness of Denver's current vulnerabilities to promote taking measures to minimize this risk before an actual earthquake or other disaster (either natural, man-made, or intentional) occurs.

Another issue investigated in this thesis is the concept of promoting inward growth, developed in the Metro Vision 2035 plan. Promoting inward growth for Denver has several benefits such as efficiency and preventing additional land development. However, as seen in figures created using ArcGIS, this inward growth increases the population density within vulnerable areas, placing more lives at risk. To add to the level of vulnerability, numerous locations where population growth percentages are expected to increase dramatically by 2035 are in designated flood zones. These issues should be recognized before implementing such development plans.

Interagency communication was another topic of interest investigated in the scope of this thesis. One of the reasons why there are so many underlying weaknesses within the infrastructure system is in part due to lack of communication in the forefront. Today, the aftermath is having to be faced, but due to the complexity of the problems associated with the infrastructures interdependencies, requiring the expertise and capabilities of every agency to be used together to face this growing issue more efficiently and effectively. The results of the survey showed that there are a few key agencies communicating the most, and these agencies should be the ones to initiate more communication among all the local, state and federal organizations. The results of the survey also displayed that population growth in the Denver Region is a topic infrequently discussed. Perhaps because population growth is not easily viewed as a stressor, the issues arising in the future as a result of the increased population density are ignored. Discussions should be made today focused on ways of minimizing potential risks and avoiding future problems, instead of waiting for discussions being made in the future on how to manage these problems.

10.2 Thesis Limitations

The purpose of examining several locations concentrated with social vulnerability and interdependencies intertwined in the Denver Region's infrastructure, subjected to natural and man-made stressors was to emphasize the existing level of risk, which will continue to rise if effective measures are not taken. It is the obligation of agencies and organizations involved in the development and maintenance of Denver's infrastructure to conduct a detailed analysis of these nodes of interdependencies and determine ways to mitigate the risk associated with each one. The level of detail of the data gathered in this study is one of the thesis's primary limitations. Data including locations of pipelines (water, natural gas, oil, etc.), electrical transmission lines, and all the critical facilities is not publicly available unless working for a government agency, due to security reasons. After the 9-11 terrorist attacks in 2001, security has been heightened, including the restricting access to specific data involving key structures, utility lines, and specific information on the types of radioactive material transported along designated routes. Agencies that have access to such data have the responsibility to proactively used it to minimize the risk associated with the development of highly interdependent systems society depends on. The amount of data is also overwhelming, requiring enough manpower and understanding of the data to properly filter and maintain it.

The second thesis limitation is the lack of technical data available concerning seismic behavior in Colorado. An appropriate attenuation function representing the Denver Region is necessary in being able to accurately predict the estimated physical and monetary damage caused by an earthquake. In this study, the attenuation function used corresponded to the Western United States attenuation zone. Based on the current data available, using this attenuation function for the earthquake scenarios is neither completely accurate nor inaccurate. The simulation still allows for the identification of vulnerable areas in the region.

The third limitation is the geographical restraint of defining a restricted study region. This study solely encompasses the effects resulting from various stressors within the Denver Region, and does not examine the interactions with the surrounding regions. A complete analysis of the consequences induced by different stressors would require a larger study region. This could pose a challenge due to time restraints and available budget. If this is the case, assumptions will need to be made to incorporate approximate input and output information to estimate losses. Finally, this thesis also does not consider or suggest a method for a cost-benefit analysis to be performed. Infrastructure planning is heavily dependent on available funding, presenting a prime opportunity to perform a cost-benefit analysis to determine where resources should be allocated to in order to receive maximum benefits.

The fourth limitation corresponds to the limitations within the program, HAZUS-MH MR4. This program uses estimated building values, employment rates, income, inventory, etc., therefore only providing an approximated loss-estimate. A more refined analysis would require significant information from local governments and agencies to supplement for the approximated values. This data is difficult to accumulate, some of which is not available to the public, and some of the data has not even been collected. Another limitation in using HAZUS is the methodologies that program uses for calculating the losses. The methodologies used are based on extensive research from several researchers, some of which can be improved in the future, but are currently the most accurate. Another limitation is that HAZUS has predefined probabilities used to estimate recovery rates, damage functions, number of people inside versus outside at a given time, etc., which the user may change. These probabilities are sufficient for making approximations, but again allow for error. Each program has limitations; these are some of the limitations within HAZUS.

10.3 Recommendations for Further Research

The scope of the research conducted in this thesis does not include examining possible solutions guided toward minimizing the geographical and social vulnerabilities extant in the Denver Region. It is important for policy makers and regional planners to recognize that the current direction of Denver’s growth patterns is continually increasing local vulnerabilities, and for them to develop policies and mitigation plans to address these issues.

Future research should also be guided toward continuing to investigate the various stressors applicable to the Denver Region. The first step in successful mitigation is to become knowledgeable about the types of potential stressors pertaining to the study area, the magnitude of these stressors in order to estimate the likely impact, and the probability of occurrence. In particular, earthquake hazards posing as a potential threat to the region need to be investigated more thoroughly. Having more concrete information about the seismicity behavior in Colorado will aid in bringing this awareness to local agencies and organizations, as well as the public, and lead to mitigation efforts to reduce the associated risks. In addition, current building and highway design codes do not represent the potential seismic forces the Denver Region could experience. The next step is to incorporate results from future research for potential seismic behavior, and for Colorado update the USGS seismic hazard maps.

Communication between agencies and organizations at the local, state and federal levels is difficult to quantify. However, similar studies with the same intention as the survey conducted in this thesis could be useful in identifying missing links of communication between these different groups. Individual efforts from each agency guided toward making the Denver community more resilient would be more effective if these efforts were conjoined by multiple agencies. This would help reduce the amount of duplicated work and open the door to better information and data sharing. Therefore, further research directed toward gaining a more detailed understanding of the level of interagency coordination would be beneficial.

Community risk is a broad and ever expanding topic, in which this thesis provides a general assessment of Denver's vulnerabilities. There are endless ideas and opportunities for future research in regard to determining methodologies of assessing risk linked to the interdependencies of infrastructure systems today and assessing the potential economic and physical effects resulting from a disaster. It is important to not turn a blind eye to the risks and vulnerabilities communities today have brought upon themselves through highly integrated infrastructure systems, but instead it is important to maintain open discussions about these issues.

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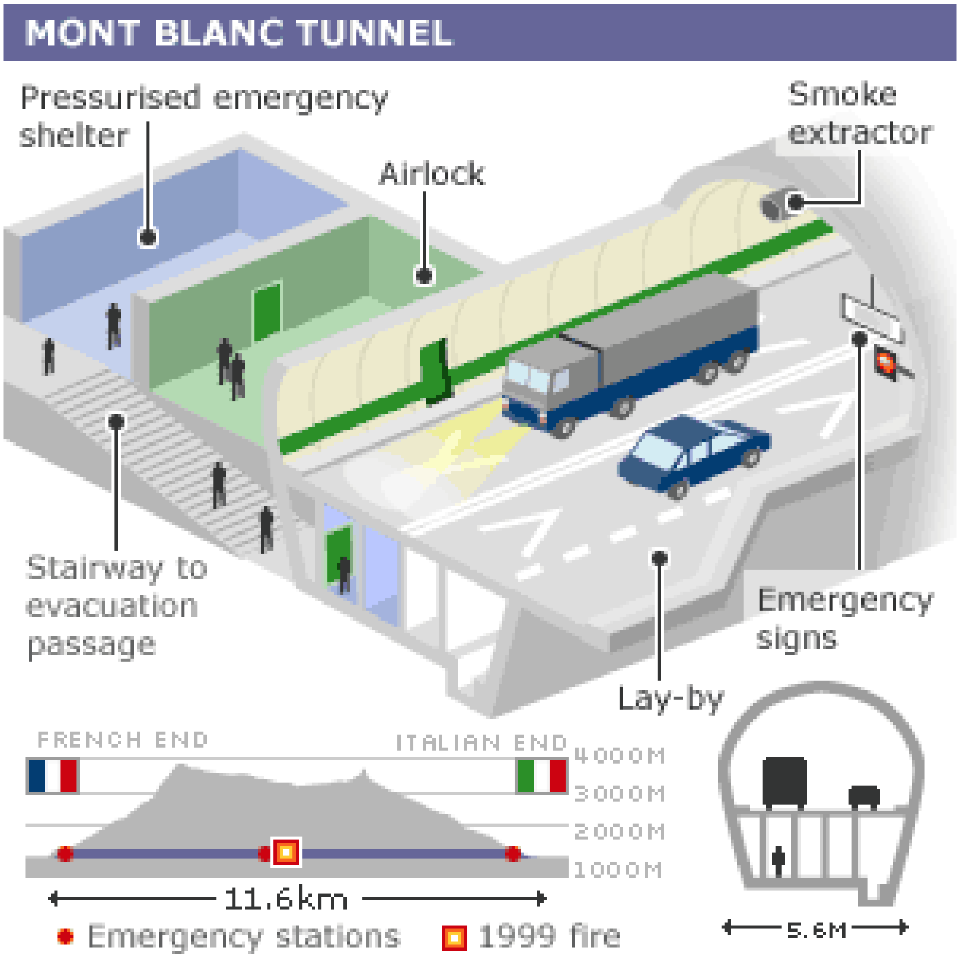
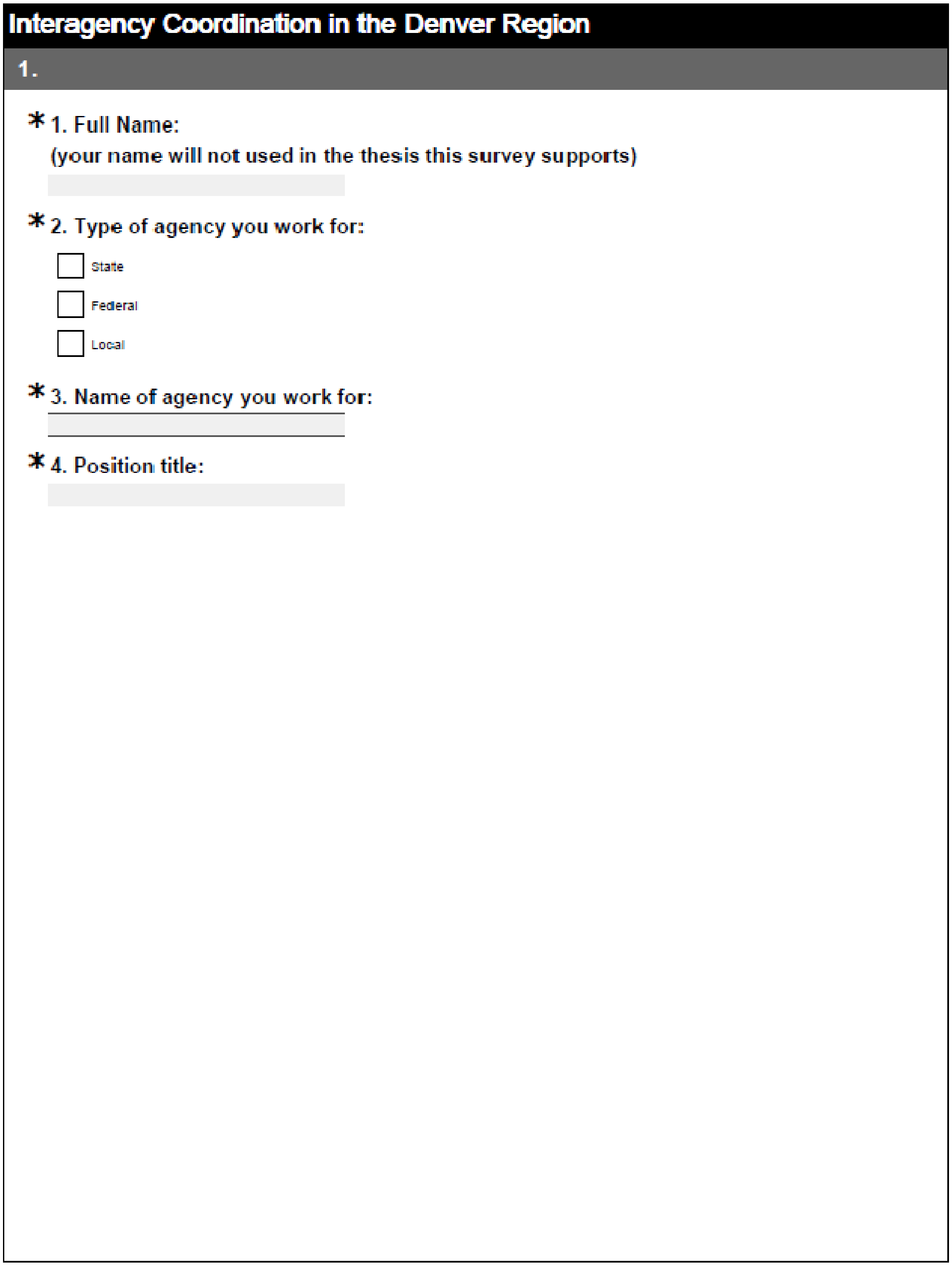
APPENDIX A: Mont Blanc Tunnel Emergency Diagram



(image from http://news.bbc.co.uk/2/hi/europe/1858436.stm)

APPENDIX B: Survey Questions



Interagency Coordination in the Denver Region

1.

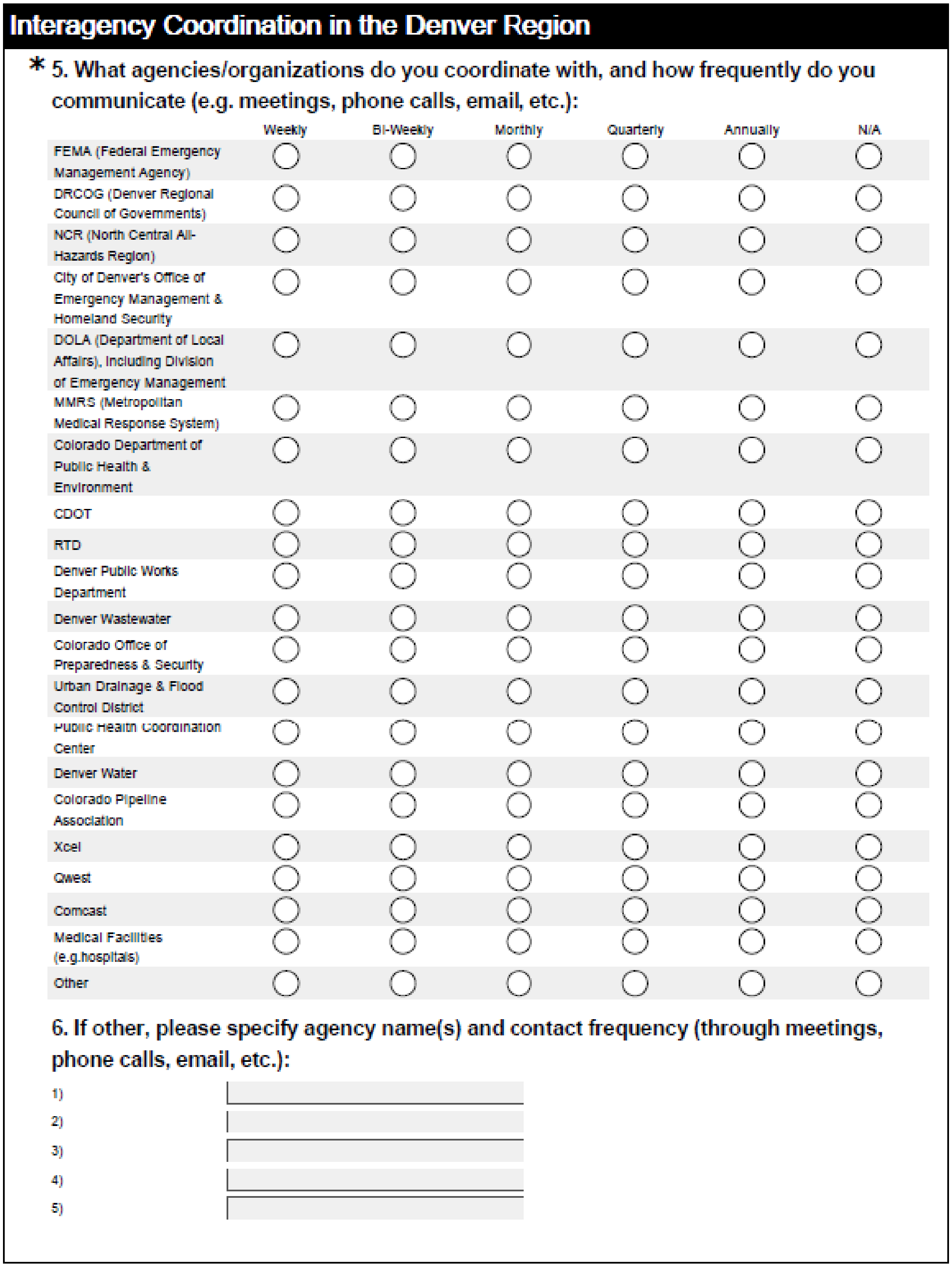
* 1. Full Name:
(your name will not used in the thesis this survey supports)

* 2. Type of agency you work for:

☐ State
☐ Federal
☐ Local

* 3. Name of agency you work for:

* 4. Position title:



Interagency Coordination in the Denver Region

* 5. What agencies/organizations do you coordinate with, and how frequently do you communicate (e.g. meetings, phone calls, email, etc.):

	Weekly	Bi-Weekly	Monthly	Quarterly	Annually	N/A
FEMA (Federal Emergency Management Agency)	○	○	○	○	○	○
DRCOG (Denver Regional Council of Governments)	○	○	○	○	○	○
NCR (North Central All-Hazards Region)	○	○	○	○	○	○
City of Denver's Office of Emergency Management & Homeland Security	○	○	○	○	○	○
DOLA (Department of Local Affairs), including Division of Emergency Management	○	○	○	○	○	○
MMRS (Metropolitan Medical Response System)	○	○	○	○	○	○
Colorado Department of Public Health & Environment	○	○	○	○	○	○
CDOT	○	○	○	○	○	○
RTD	○	○	○	○	○	○
Denver Public Works Department	○	○	○	○	○	○
Denver Wastewater	○	○	○	○	○	○
Colorado Office of Preparedness & Security	○	○	○	○	○	○
Urban Drainage & Flood Control District	○	○	○	○	○	○
Public Health Coordination Center	○	○	○	○	○	○
Denver Water	○	○	○	○	○	○
Colorado Pipeline Association	○	○	○	○	○	○
Xcel	○	○	○	○	○	○
Qwest	○	○	○	○	○	○
Comcast	○	○	○	○	○	○
Medical Facilities (e.g.hospitals)	○	○	○	○	○	○
Other	○	○	○	○	○	○

6. If other, please specify agency name(s) and contact frequency (through meetings, phone calls, email, etc.):

1)

2)

3)

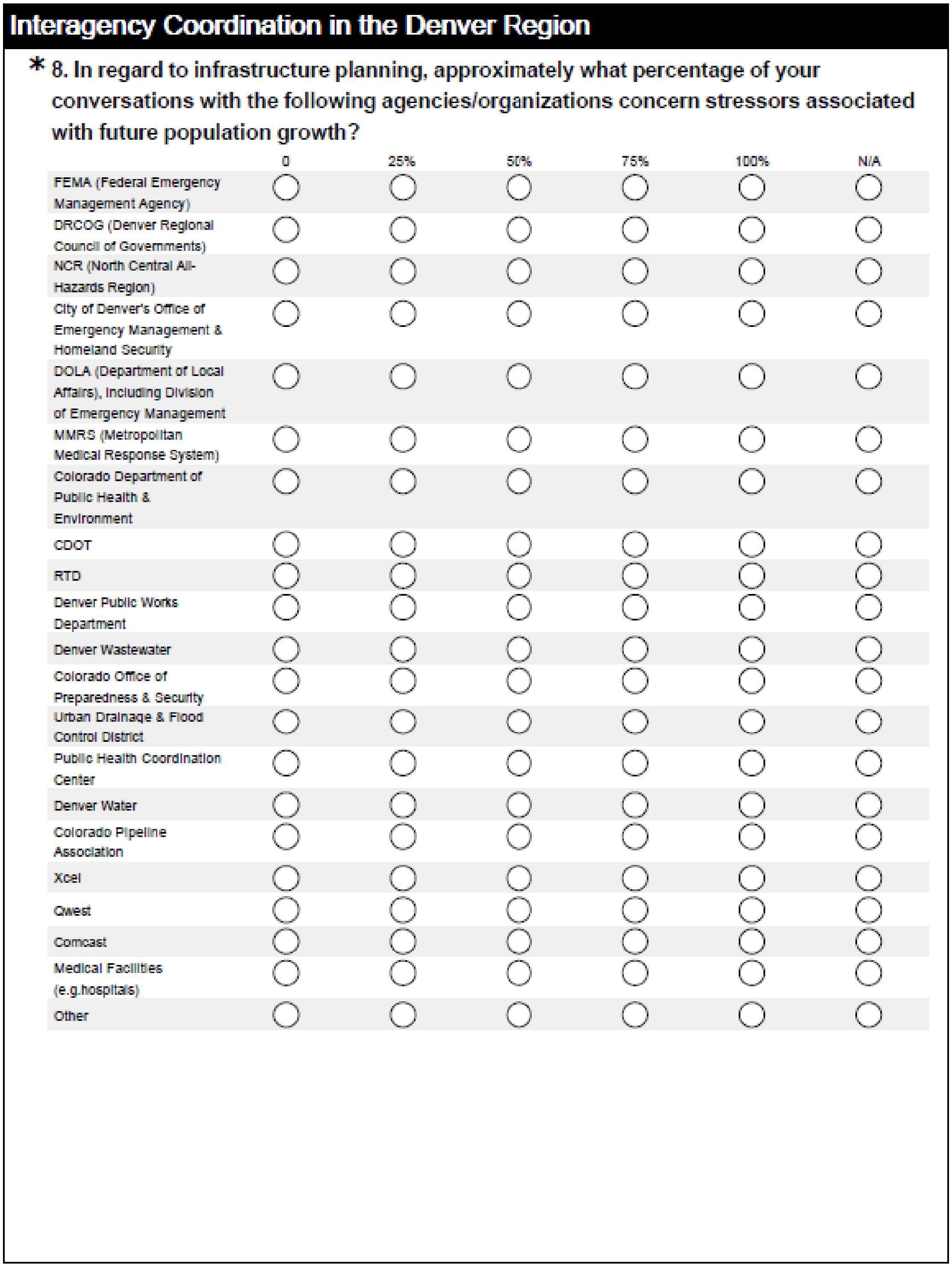
4)

5)

Interagency Coordination in the Denver Region

*** 7. In regard to infrastructure planning, approximately what percentage of your conversations with the following agencies/organizations include the potential impact of natural disasters, man-made hazards, and/or intentional attacks?**

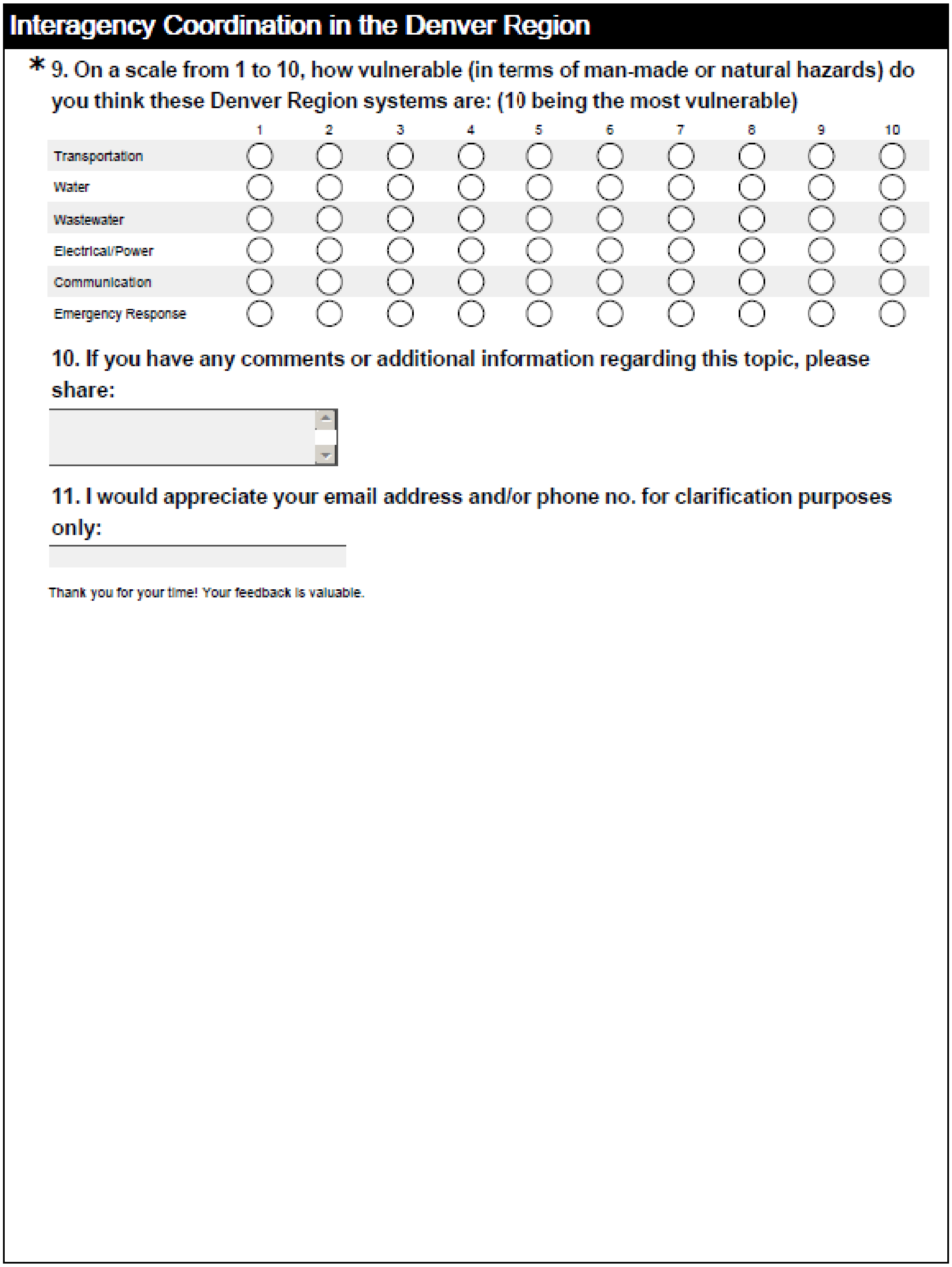
	0%	25%	50%	75%	100%	N/A
FEMA (Federal Emergency Management Agency)	○	○	○	○	○	○
DRCOG (Denver Regional Council of Governments)	○	○	○	○	○	○
NCR (North Central All-Hazards Region)	○	○	○	○	○	○
City of Denver's Office of Emergency Management & Homeland Security	○	○	○	○	○	○
DOLA (Department of Local Affairs), including Division of Emergency Management	○	○	○	○	○	○
MMRS (Metropolitan Medical Response System)	○	○	○	○	○	○
Colorado Department of Public Health & Environment	○	○	○	○	○	○
CDOT	○	○	○	○	○	○
RTD	○	○	○	○	○	○
Denver Public Works Department	○	○	○	○	○	○
Denver Wastewater	○	○	○	○	○	○
Colorado Office of Preparedness & Security	○	○	○	○	○	○
Urban Drainage & Flood Control District	○	○	○	○	○	○
Public Health Coordination Center	○	○	○	○	○	○
Denver Water	○	○	○	○	○	○
Colorado Pipeline Association	○	○	○	○	○	○
Xcel	○	○	○	○	○	○
Qwest	○	○	○	○	○	○
Comcast	○	○	○	○	○	○
Medical Facilities (e.g.hospitals)	○	○	○	○	○	○
Other	○	○	○	○	○	○



Interagency Coordination in the Denver Region

* 8. In regard to infrastructure planning, approximately what percentage of your conversations with the following agencies/organizations concern stressors associated with future population growth?

	0	25%	50%	75%	100%	N/A
FEMA (Federal Emergency Management Agency)	○	○	○	○	○	○
DRCOG (Denver Regional Council of Governments)	○	○	○	○	○	○
NCR (North Central All-Hazards Region)	○	○	○	○	○	○
City of Denver's Office of Emergency Management & Homeland Security	○	○	○	○	○	○
DOLA (Department of Local Affairs), including Division of Emergency Management	○	○	○	○	○	○
MMRS (Metropolitan Medical Response System)	○	○	○	○	○	○
Colorado Department of Public Health & Environment	○	○	○	○	○	○
CDOT	○	○	○	○	○	○
RTD	○	○	○	○	○	○
Denver Public Works Department	○	○	○	○	○	○
Denver Wastewater	○	○	○	○	○	○
Colorado Office of Preparedness & Security	○	○	○	○	○	○
Urban Drainage & Flood Control District	○	○	○	○	○	○
Public Health Coordination Center	○	○	○	○	○	○
Denver Water	○	○	○	○	○	○
Colorado Pipeline Association	○	○	○	○	○	○
Xcel	○	○	○	○	○	○
Qwest	○	○	○	○	○	○
Comcast	○	○	○	○	○	○
Medical Facilities (e.g.hospitals)	○	○	○	○	○	○
Other	○	○	○	○	○	○



Interagency Coordination in the Denver Region

* 9. On a scale from 1 to 10, how vulnerable (in terms of man-made or natural hazards) do you think these Denver Region systems are: (10 being the most vulnerable)

	1	2	3	4	5	6	7	8	9	10
Transportation	○	○	○	○	○	○	○	○	○	○
Water	○	○	○	○	○	○	○	○	○	○
Wastewater	○	○	○	○	○	○	○	○	○	○
Electrical/Power	○	○	○	○	○	○	○	○	○	○
Communication	○	○	○	○	○	○	○	○	○	○
Emergency Response	○	○	○	○	○	○	○	○	○	○

10. If you have any comments or additional information regarding this topic, please share:

11. I would appreciate your email address and/or phone no. for clarification purposes only:

Thank you for your time! Your feedback is valuable.

APPENDIX C: List of Participating Agencies and Position Titles of Survey Participants

1	FEMA
2	Town of Castle Rock
3	City of Commerce City
4	City of Lakewood
5	CDOT
6	North Central Region
7	CDOT
8	Regional Air Quality Council
9	Federal Highway Administration
10	Denver Regional Council of Governments
11	Devner Technology Services Agency
12	Douglas County Government & Sheriff's Office
13	Denver Public Health
14	North Washington Fire Protection District
15	Greenwood Village Police
16	FEMA
17	CO Dept of Public Health & Environment
18	South Metro Fire Rescue Authority
19	Denver Fire Department
20	Denver Office of Emergency Management and Homeland Security
21	Tri-County Health Department
22	City and County of Denver, Mayor's Office of Emergency Management and Homeland Security
23	City & County of Denver
24	City of Arvada Police Department
25	University of Colorado Denver
26	City of Thornton
27	FEMA
28	FEMA Region VIII
29	City of Englewood
30	CDOT