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A Simulation-Based Analysis of Chemical and Radiological Hazard Zones Adapted to Physical Boundaries

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THESIS

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Abstract

In the United States, industrial and terrorist use of chemical, biological, radiological, and nuclear (CBRN) materials pose a risk to public safety. During the initial phase of typical CBRN incidents, emergency responders establish hazard zones based on standard distances from published guidelines and recommendations. This research investigates how standard hazard zones change in a real world environment that accounts for physical boundaries. Using a python simulation in ArcGIS®, new hazard zones were created by expanding standard hazard zones to follow nearby roads, railroads, and rivers. The new and standard zones were compared by calculating the population and area affected by each zone. Additionally, responder efficiency was compared across different combinations of physical boundaries. The simulation generated 990 random points across three cities and three environments (urban, suburban, rural) and was replicated for six hazards. The results revealed significantly larger populations and areas affected by new zones compared to standard zones and significant effects from the environment and city where the incident occurred. Depending on hazard, the median growth ranged from approximately 340 to 8,000 people and 0.6 to 8.8 square miles. The particular combination of physical boundaries used in creating hazard zones was not found to influence responder efficiency.

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I. Introduction

Background

Chemical, biological, radiological, nuclear, and high-yield explosives (CBRNE) incidents have posed a threat to the public's safety for centuries. A large range of industries across the United States currently use toxic industrial chemicals and materials (TIC/TIMs). Over 20,000 facilities release or dispose of toxic chemicals as part of their normal operations every year (U.S. Environmental Protection Agency (EPA), 2015). As might be expected, spills and accidental releases are common. In 2014, the National Response Center tracked reports of more than 30,000 chemical incidents and over 1,100 fatalities (U.S. Coast Guard, 2015). Nuclear power plants have raised more recent concerns about accidents releasing radioactive material. The first nuclear power plant in the United States began operating in 1957, and today there are 99 nuclear power reactors in operation at 62 locations (U.S. Nuclear Regulatory Commission, 2015). Widely considered the most serious nuclear accident in U.S. history, Three Mile Island experienced a partial meltdown in 1979. While only a voluntary evacuation notice was issued, it is estimated that 144,000 people evacuated the area (Stallings, 1984). Hazardous chemical and biological agents have also been used intentionally as weapons for millennia; ancient Chinese and Greek writings describe acts of war involving contaminated water supplies and toxic sulfur fumes (Chauhan, 2008). Chemical weapons, while not new, were first used on a large scale in World War I (Szinicz, 2005). Nuclear weapons and radiological dispersal devices have posed more recent threats regarding radiological fallout. A small nuclear attack in a city could impact thousands of square kilometers and hundreds of thousands of people (Federal Emergency Management Agency (FEMA), 2008). In the last century, this threat has grown considerably, and terrorism has expanded the concern of intentional releases beyond the battlefield.

Current Response Guidelines

In the United States, local, state, and national government agencies need to be prepared to respond to a CBRNE incident in many types of environments. Several federal agencies, such as the EPA, U.S. Department of Transportation (DOT), and FEMA, have worked to establish response guidelines. For example, the U.S. DOT, Transport Canada, and Secretariat for Communications and Transportation (2012) have published documents discussing the zones that should be evacuated or cordoned off for transportation accidents, FEMA has provided recommendations for the evacuation vs. shelter-in-place decision for airborne hazardous materials accidents (Buddemeier, Valentine, Millage, & Brandt, 2011), and the EPA (2013) has researched radiation dose limits to provide protection from adverse health effects. Additionally, much research has been done to refine these recommendations, better understand the hazards involved, and propose new response strategies (cf. Dillon, 2014; Sorenson, 2004; Chakrabarti & Parikh, 2013; Wein, 2010; Lindell, 2000; EPA, 2013; Glickman & Ujihara, 1990).

There are accepted standards and guidelines for responding to many types of CBRNE incidents. These guidelines include procedures for setting up hazard zones at defined distances around the incident or plume during the initial phase (i.e. typically about the first 30 minutes) of the response (Chakrabarti & Parikh, 2013). A widely used reference in North America is the DOT's Emergency Response Guidebook (2012), which recommends initial isolation and protective action distances for different chemicals and situations. The initial isolation zone is the area directly around the incident within which the concentration is expected to be lethal or dangerous and is restricted to emergency responders wearing appropriate protective equipment. The protective action zone is the area in the downwind direction within which the concentration is expected to cause debilitating or serious injury. Typically, responders would direct evacuation or shelter-in-place within the protective action zone. However, in practice, responders must deal with the physical boundaries of the environment at the incident site, such as roads, buildings, railroads, forests, and rivers. Little research has been done to quantify the effect of physical boundaries on hazard zones. Some responders might set up a cordon that matches as closely as possible to the recommended distances without specific consideration for physical boundaries, whereas other responders might try to conform to nearby natural and infrastructure boundaries.

Additionally, the effects of the physical environment on a hazard or evacuation zone might change from one location to another. For example, an urban location has more man-made boundaries, such as roads, buildings, and utilities, whereas a rural environment typically has more natural boundaries, such as rivers, hills, and woodlands. While a CBRNE incident is unlikely in a location with no man-made infrastructure, an incident can occur in areas with substantial infrastructure or with very little infrastructure. For example, a truck transporting hazardous materials on a small highway in the middle of Wyoming and a dirty bomb in downtown New York City are both plausible scenarios. Because population density varies among environments, the incident environment has a significant impact on the number of people evacuated or otherwise affected by an incident. The available physical boundaries might also affect responder efficiency in establishing cordons. For example, a cordon that requires more road blocks will take longer to establish and more manpower to maintain.

Many guidelines are based on “bright lines,” or the idea that there is a specific threshold under which no adverse effects are expected. However, in reality, these thresholds contain a good deal of uncertainty. In some incidents, the bright line might be insufficient to protect the public, and in many incidents, the bright line might be more conservative than necessary (Thompson, 2002), contributing to uncertainty in the standard distances at which to establish cordons. Bright lines also might not be publicly accepted. If buildings on one side of a street are evacuated, but the other side is deemed safe, people might resist evacuating or decide to self-evacuate, which can aggravate transportation networks and place additional demands on emergency responders and mass care resources.

Historical Example

On 6 January 2005, a train carrying hazardous materials collided with another train in Graniteville, South Carolina. Several of the cars derailed, including three containing chlorine. One of the railcars was punctured and released approximately 60 tons of chlorine. The release resulted in 9 deaths, 554 respiratory complaints, and 75 hospital admissions. About 5,400 people were evacuated within a one-mile radius for the next several days while responders contained the site and removed the hazardous materials.

The conditions at the time of the incident (2:39 am) included moderate winds at 7 mph from the south-southwest and clear skies (NTSB, 2005). Under these conditions for a rail car spill, the 2012 Emergency Response Guidebook (ERG) recommends a 3,000-foot initial isolation zone and at least 7-mile protective action zone in the downwind direction (DOT et al., 2012). The 2004 ERG, which was current at the time of the Graniteville incident and did not include detailed recommendations for wind speeds or type of spill, recommended an 800-foot initial isolation zone and 4.6-mile protective action zone (DOT et al., 2004). However, the emergency responders set up hazard zones and protective actions using different distances. Within 10 minutes of the accident, the fire chief directed that residents be notified to shelter in place. Within 20 minutes, approach roads were blocked to restrict traffic within a radius of about one mile. The sheriff's office later ordered an evacuation of residents within a one-mile radius and implemented an almost 1,000-foot zone around the accident site where only personnel wearing personal protective equipment were allowed access (NTSB, 2005). Additionally, a curfew was implemented for residents between one and two miles from the accident (Mitchell at al., 2005).

A survey conducted shortly after the accident found that there was some confusion among residents regarding the evacuation order. Almost all residents who lived within one mile evacuated, but about 59% of residents between one and two miles also decided to evacuate. Many of these residents thought the evacuation order applied to them, some were unsure, and some decided to evacuate even though they understood the order did not apply to them. Several residents indicated that they were unclear about the exact boundaries and would have liked to see street names demarking the boundaries on the maps shown on the news (Mitchell et al., 2005). The evacuation behavior during this incident illustrates the challenge faced by responders and community officials when they implement hazard zones in a real world environment, namely determining and clearly communicating the precise boundaries of the zones.

Hazards

FEMA categorizes hazards as natural, technological, or human-caused. While natural disasters can trigger CBRNE accidents (Burdick, 2005), technological or human-caused hazards are more likely to directly cause a CBRNE incident. Every technological system has the potential to fail and cause an accident. Thousands of TIC/TIMs are used in various industrial processes across the country, which could accidentally release a hazardous substance. Some TIC/TIMs pose a particular risk to inhalation and are referred to as Toxic Inhalation Hazards (TIHs). The DOT et al. have identified six TIHs that are more commonly encountered in accidental releases (DOT et al., 2012), three of which are studied in this research. Human-caused hazards include chemical and biological agents used as weapons, nuclear weapons, and radiological dispersal devices (RDDs). Chemical agents are further categorized as nerve, blister, choking, and blood agents. Nerve agents are especially toxic and fast-acting. RDDs are of particular concern as a terrorist threat. This research considers two nerve agents and one RDD of unknown size, material, and geometry.

Problem Statement

The purpose of this research is to investigate and characterize initial emergency hazard zones for CBRNE incidents in a real world scenario by accounting for the physical environment.

Research Questions

The following three research questions were investigated:

1. How do published emergency hazard zones for various CBRNE incidents change when adapted to physical boundaries?

2. What effects do different environments and locations have on emergency hazard zones when the zones are adapted to physical boundaries?

3. Is there a preferred set of physical boundaries that improves responder efficiency?

Methodology

The methodology employed in this research consisted of selecting incident locations to use for case studies, developing a model with ESRI's ArcGIS® 10.2 software (2014) to generate hazard zones and population data, and performing statistical analysis to compare the standard zones to the zones considering physical boundaries.

Hazard and Location Selection

Three TIC/TIM hazards (anhydrous ammonia, chlorine, and sulfur dioxide), two chemical warfare hazards (VX and sarin), and one radiological hazard (radiological dispersal device) were selected for analysis. Standard hazard distance guidelines from the Emergency Response Guidebook were determined for the TIC/TIM and chemical warfare hazards. Standard hazard zone distances were determined for radiological dispersal devices from Sandia National Laboratory experiments (Musolino, Harper, Buddemeier, Brown, & Schlueck, 2013). Three areas within the United States (Chicago, Denver, and Houston) were chosen to reflect areas where releases are relatively common. Three locations within each metropolitan area were further selected to consider the impact of urban, suburban, and rural environments.

ArcGIS® Model

Geospatial analysis was used to generate standard cordons and evaluate their impacts on population and area. An algorithm was developed to adjust the standard cordons to match boundaries in the physical environment, and geospatial analysis was again used to evaluate the new impacts on population and area. The physical boundaries selected were roads, railroads, and rivers. Hazard distances were not allowed to decrease, so the resulting hazard zones covered an equal or greater total area to prevent accepting additional risk to the population. As a measure of responder efficiency, the number of intersections in the new hazard zones using four different combinations of physical boundaries was also counted and compared to the standard zones. These intersections represent locations where responders might have to block traffic and serve as a proxy variable for the complexity of the zones.

Statistical Analysis

Each of the 6 hazards was modeled in each of the 9 locations, resulting in 54 scenarios. Each scenario was repeated 110 times by randomly generating specific release sites within a defined region. In total, 5,940 observations were generated in this investigation. Data representing the area and population affected by the hazard zones were collected for each iteration. Additionally, the number of hazard zone intersections was used as a proxy variable to measure responder efficiency. Paired t-tests, confidence intervals, ANOVAs, and a select-the-best procedure were used to compare the paired scenarios based on the collected data.

Assumptions/Limitations

One significant limitation of this study is that responders respond differently; in other words, the same scenario could lead to different decisions regarding cordon set-up. This bias may be influenced by multiple factors including experience and available resources. Additionally, this research only looked at three locations and only considered six hazards or threats in certain meteorological conditions. The ERG is mostly used for accidental releases, so worst-case scenarios involving intentional or catastrophic releases of TIC/TIMs may require larger distances. The section of the ERG used in this research is also limited to airborne hazards and does not consider the effects of contamination that may spread along the ground or by water. Further, there may be other elements of the physical environment that influence hazard boundaries that were not included in this study, such as hills or low-lying areas, property boundaries, jurisdictional designations, and woodlands. Finally, the estimated populations affected by the hazard zones relied on U.S. Census Bureau's census block data. Thus, the populations were estimated from places of residence and will not always reflect the actual presence of people during an incident in an area, as people work, shop, and travel to different places.

Implications

Currently, responders operate with initial hazard zone recommendations that do not explicitly account for the physical environment. Responders generally rely on judgement and personal experience to apply the recommendations to the real world incident. Many characteristics of a specific scenario can vary, such as population density, environment, road networks, and city. The implications of the process of setting up real world hazard zones from general recommendations are largely unknown. However, understanding the extent of area and people affected by the real world application of hazard zones is an important input for protective action and resource management decisions. Additionally, researchers and community leaders who use simplified, generic hazard zones during pre-planning to evaluate response protocols, evacuation decision points, and hypothetical incident impacts to the population often rely on their results to develop critical plans and tools and make resource decisions. It is imperative that they be equipped with estimates that are as accurate as possible.

Preview

This thesis consists of five chapters. The first chapter provided background information and established the research questions. The second chapter will review literature relevant to the research. The third chapter will describe the methodology applied to the problem. The fourth chapter will explain the results of the analysis. The final chapter will provide conclusions from the study and answer the research questions.

II. Literature Review

Introduction

Within the all-hazards framework, FEMA categorizes hazards into three types. Natural hazards are caused by acts of nature, and while they could result in CBRN releases, they are not directly considered in this research. Technological hazards are caused by system failures. These include industrial chemical and nuclear power accidents. An industrial chemical accident might involve the release of any hazardous materials used for industrial purposes, commonly known as Toxic Industrial Chemicals and Toxic Industrial Materials (TIC/TIM). A nuclear industry accident may involve the release of radiological material. Finally, human-caused hazards are caused by intentional acts. These include chemical, biological, and radiological agents intentionally released as weapons, which would typically be considered an act of terrorism within the United States. Once a hazardous material release occurs, response agencies must manage the incident to control the hazard. This chapter will consider potential technological and human-caused hazards. Additionally, typical incident response management protocols, factors affecting the decision to evacuate or shelter-in-place, exposure guidelines, and standard hazard zone determinations and recommendations will be addressed.

Technological Hazards – TIC/TIMs

A frequent technological hazard is the accidental release of industrial chemicals. The U.S. Department of Transportation (DOT) (2012) lists six chemical hazards that are commonly encountered in accidental releases. These are anhydrous ammonia, chlorine, ethylene oxide, hydrogen chloride, hydrogen fluoride, and sulfur dioxide. These six have a "high" hazard index, indicating that the hazard is widely produced, transported, or stored and has high toxicity and volatility (Fatah et al., 2001). While TIC/TIMs can be intentionally released in an attack with the same physiological consequences, releases are more commonly associated with accidents. To select industrial hazards for this research, data from the National Response Center (U.S. Coast Guard, 2015), which tracks reports of hazardous materials and oil spills, were analyzed. From 2012 to 2014, there were 2,501 ammonia releases, 593 sulfur dioxide releases, 302 chlorine releases, 54 ethylene oxide releases, 30 hydrogen chloride releases, and less than 20 hydrogen fluoride releases. As the most commonly released chemicals of the six toxic inhalation hazards identified by the DOT, ammonia, sulfur dioxide, and chlorine were studied. These chemicals provide a sufficient range of possible scenarios.

Anhydrous Ammonia

Ammonia is a chemical that is made up of nitrogen and hydrogen. In a purely gaseous state with no water, it is called anhydrous ammonia. Ammonia has no color, but does have a strong distinct odor. Ammonia is lighter than air, but if transported or stored as compressed liquefied gas, an initial spill may result in a fog that stays low to the ground. It is produced by both nature and manufacturing and is only dangerous in concentrated forms. It is most commonly used in fertilizer, as well as cleaning solutions and the manufacture of various products. In 2002, 10.8 million metric tons of ammonia were manufactured in the United States at over 2,300 facilities, making it one of the most highly produced chemicals in the country. More than half the ammonia production in the United States occurs in Louisiana, Oklahoma, and Texas (ATSDR, 2004).

Exposure to anhydrous ammonia can occur through inhalation, ingestion, or skin contact. It is primarily an upper respiratory irritant. Ammonia reacts with water to form ammonium hydroxide, which is strongly alkaline and corrosive. Contact with concentrated ammonia can cause severe burns to any tissue with moisture, such as the lungs, eyes, and skin. Ammonia has a particularly strong affinity for damaging the eyes. Severe exposures can lead to permanent injury, blindness, or death, which usually results from pulmonary edema (Chemical Hazards Emergency Medical Management (CHEMM), 2014). Ammonia is detectable by odor at around 5 ppm. At concentrations above about 50 ppm, people will typically experience irritation in the nose and throat, and at around 100 ppm, people will experience slight eye irritation. Most people can tolerate concentrations of around 250 ppm for 30-60 minutes (ATSDR, 2004; Public Health England, 2015). The immediately dangerous to life and health (IDLH, discussed in detail later in this chapter) concentration is 300 ppm (NIOSH, 2011).

Chlorine

Chlorine is a gas with a greenish-yellow color and strong odor. Chlorine is highly reactive and unstable. Chlorine is heavier than air, so it tends to remain low to the ground. It is usually transported as a liquid under pressure by tanker trucks or as a liquid or gas through pipelines. In 2008, 10.6 million metric tons of chlorine were produced in the United States. The primary uses of chlorine are in manufacturing of PVC plastics, other organic compounds, and inorganic chemicals, as well as water treatment (ATSDR, 2010). In 1915 at Ypres, Belgium, chlorine was the first chemical to be used as a weapon of mass destruction (Szinicz, 2005). Since then, more toxic chemicals have been developed for use in war, but given the accessibility and prevalence of chlorine in industrial applications, chlorine could be used for a domestic terror attack (Barrett & Adams, 2011).

Exposure to chlorine gas can irritate the respiratory tract and eyes and affect pulmonary function. Chlorine reacts with moisture in the cells of the respiratory tract and other surfaces to produce hydrochloric acid and hypochlorous acid. The hypochlorous acid decomposes to form oxygen free radicals, which are highly corrosive (Banks, 2014). The IDLH concentration is 10 ppm, above which a person's ability to escape may be hampered (NIOSH, 2011). At a concentration of 15 ppm, most people experience irritation in the nose, eyes, and throat. Chest pain and coughing occur at around 30 ppm. Toxic pneumonitis and pulmonary edema occur at around 40-60 ppm. Death can be expected after a few minutes of exposure at about 1,000 ppm. The duration of exposure and the presence of respiratory conditions affect the symptoms and the concentrations at which symptoms occur (ATSDR, 2010).

Sulfur Dioxide

Sulfur dioxide is a gas with a strong odor and no color that dissolves readily in water and is heavier than air. Sulfur dioxide exists in the atmosphere as a result of fuel combustion, industrial processes, and volcanic activity. Sulfur dioxide is commonly produced commercially by burning elemental sulfur. Most commercial sulfur dioxide is produced as part of the process of manufacturing sulfuric acid, wood pulp, and paper, as well as smelting operations. It is also used in preservatives, refrigeration, bleach, and other industrial processes. In 1985, 118,000 metric tons of sulfur dioxide were produced (ATSDR, 1998).

Exposure to sulfur dioxide can occur through inhalation, ingestion, or skin contact. Like ammonia and chlorine, it primarily affects the respiratory system. Sulfur dioxide reacts with water to form sulfites, which systemically travel through the blood. Sulfites can be oxidized to sulfite oxidase in the liver and excreted through urine. Inhalation of sulfur dioxide causes bronchoconstriction, leading to increased airway resistance. Contact with sulfur dioxide can cause burns to any tissue with moisture, such as the lungs, eyes, and skin. Severe exposures can lead to permanent injury or death (ATSDR, 1998). Sulfur dioxide is detectable by odor at around 3 to 5 ppm. At concentrations around 8 to 12 ppm, people will typically experience irritation in the eyes and throat, and at around 50 ppm, people often experience severe irritation. The IDLH concentration has been established at 100 ppm by NIOSH (2011). Concentrations around 400 to 500 ppm are considered immediately life-threatening (U. S. National Library of Medicine (NLM), 2015).

Human-Caused Hazards

Human-caused CBRN attacks have historical precedence both as weapons of mass destruction in warfare and as targeted terrorist attacks. In World War I, chemicals were used extensively on the battlefield. The first use of a chemical agent as a weapon of mass destruction was chlorine in 1915. Phosgene was first used later that year, is ten times as toxic as chlorine, and had the highest mortality rate from chemical weapons in World War I (Szinicz, 2005). Mustard gas was first used in 1917 and proved effective against troops wearing protective masks, causing approximately 27,000 casualties before the end of the war. Estimates vary, but approximately 1,000,000 casualties and 80,000 fatalities resulted from chemical warfare agents in World War I (Joy, 1997). In World War II, Japan used choking and blister agents, as well as biological agents, during the invasion of China. While not used in war, Germany used blood agents in concentration camps (Szinicz, 2005). Nuclear weapons were first used in warfare when the United States detonated two atomic bombs over Japan in 1945. A 15 kiloton yield nuclear weapon was detonated over Hiroshima, and a 21 kiloton yield nuclear weapon was detonated over Nagasaki (Woodruff, Alt, Forcino, & Walker, 2012).

In recent decades, CBRN agents have also been involved in terrorist attacks. In 1995, a terrorist group in Tokyo released sarin in five subway cars on three lines during rush hour, resulting in 11 deaths and over 5,000 casualties (Okumura, 1996). In 2001, letters contaminated with anthrax spores infected 22 people and killed 5 (Bush & Perez, 2012). In 2014, an attack near Damascus, Syria involved sarin. Death toll estimates range from about 350 to 1,500 (Pita & Domingo, 2014).

Chemical Agents

Chemical agents are categorized as nerve, blister, choking, and blood agents. Each category is briefly discussed in this section. Due to their high toxicity, this research will consider VX and GB (sarin). VX and sarin have substantially different properties. VX is non-volatile and doesn’t boil until 298 degrees Celcius, contributing to its high persistency in the environment. VX is highly toxic with an AEGL-1 (acute exposure guideline level indicating the concentration above which non-disabling, temporary health effects can be expected) at 10 minutes of 0.000052 ppm. Comparatively, sarin has a volatility about 4 orders of magnitude greater than VX and a lower boiling point of 147 degrees Celcius, contributing to its lack of persistence in the environment. Sarin has a toxicity level about 100 times lower than VX with an AEGL-1 at 10 minutes of 0.012 ppm. These differences are also evident in the differing hazard distances discussed later in this chapter.

Nerve Agents

Nerve agents are organophosphates that affect the nervous system. Exposure to nerve agents is most commonly by inhalation, but can also occur through skin contact or ingestion. Nerve agents include VX and G-series agents, such as sarin, tabun, and soman. According to Szinicz (2005), "VX appears to be the most effective chemical warfare agent ever produced." A dose of approximately 0.3 mg by inhalation and a dose of approximately 5 mg by dermal exposure are considered lethal (Szinicz, 2005). VX is an oily liquid with a low volatility, so it has high persistence in the environment. Sarin has a high volatility, so the liquid more quickly evaporates and dissipates from the immediate environment.

Nerve agents act by inhibiting acetylcholinesterase from breaking down acetylcholine. This results in an excess of acetylcholine at cholinergic terminals. Acetylcholine is used more in the parasympathetic division than the sympathetic division, so the parasympathetic system is affected to a greater degree. The muscles triggered by acetylcholine cannot stop contracting, so they quickly fatigue, causing weakness, failure, and eventual paralysis. Clinical manifestations include miosis, eye pain, chest tightness, muscle weakness, nausea/vomiting, coughing, shortness of breath, loss of consciousness, paralysis, and tachycardia. Fatigue of vital organs, such as the lungs, leads to death. These effects can be seen within minutes after inhalation and within a few hours after contact with the liquid (Burke, 2003; Weinbroum, 2005).

Blister agents

Blister agents are chemicals that burn tissue and cause blistering. Exposure occurs through contact with skin or mucous membranes. Blister agents commonly include sulfur mustard and lewisite. Mustard is an oily substance with an odor of mustard or garlic, is heavier than air, and has low volatility. Lewisite is a colorless liquid with a metallic taste and is less stable than mustard (Ganesan, Raza, & Vijayaraghavan, 2010). These agents have low fatality rates estimated at 2-5%, but high morbidity rates. In World War I, mustard made up the greatest portion of chemical weapon casualties at about 70%, but only a small portion of deaths (Chauhan et al., 2008).

Mustard acts by degrading DNA, protein, and other molecules, which effectively inhibits protein synthesis and kills the cells. Fast dividing cells, such as epithelial and bone marrow cells, are most affected. At lower severity, clinical manifestations include eye itching and burning, coughing, and skin reddening. At higher severity, clinical manifestations include vesication, skin necrosis, corneal inflammation and scarring, sloughing of airway mucosa, and shortness of breath. In the case of mustard, effects are typically delayed a few hours after exposure, whereas the effects of lewisite occur almost immediately (Ganesan, Raza, & Vijayaraghavan, 2010). Lewisite is also a systemic toxin and can cause symptoms such as pulmonary edema, low blood pressure, and weakness (Burke, 2003). Mustard can reduce blood cells counts 5-10 days after exposure. Early fatalities usually result from laryngospasm, fatalities within a few days are usually caused by secondary pneumonia, and delayed fatalities are usually caused by bone marrow suppression (Chauhan et al., 2008).

Choking agents

Choking agents are chemicals that damage the lungs and respiratory tract. They react with moisture to create corrosive compounds that damage lung tissue and can cause death by pulmonary edema. Exposure can occur through inhalation, skin contact, and ingestion. Choking agents that have been historically weaponized include chlorine, phosgene, and diphosgene. Chlorine is a greenish-yellow gas, phosgene is a white gas, and both are heavier than air (McCafferty & Lennarson, 2002). Approximately 80% of chemical weapon fatalities in World War I were due to phosgene (Ganesan, Raza, & Vijayaraghavan, 2010).

Choking agents react with water to form acidic or basic compounds. Chlorine forms hydrochloric acid and oxygen free radicals, whereas phosgene forms hydrochloric acid and carbonyl (Cashman, 2008). As noted under chlorine earlier, clinical manifestations include eye irritation, coughing, chest pain, shortness of breath, and pulmonary edema. While effects from chlorine can be evident within minutes of exposure, effects from phosgene may be delayed several hours. Clinical manifestations are similar and include shortness of breath, bradycardia, hypotension, nausea, and pulmonary edema (Ganesan, Raza, & Vijayaraghavan, 2010). Phosgene has an odor of freshly mown hay, but the concentration at which the odor is detectable is several times higher than the permissible exposure level.

Blood agents

Blood agents are chemicals that cause chemical asphyxiation by inhibiting the blood's ability to transport or use oxygen. Blood agents are volatile liquids or gases and are thus non-persistent (Burke, 2003). Blood agents include nitrites, carbon monoxide, hydrogen cyanide, and hydrogen sulfide. While the least toxic of the chemical warfare agents, the effects of blood agents occur within seconds to minutes. Several blood agents were first used as industrial chemicals before being applied as weapons (Ganesan, Raza, & Vijayaraghavan, 2010). France used hydrogen cyanide in World War I, but its high evaporation rate made it less effective. It has been used in both Germany and Iraq for extermination (Chauhan et al., 2008).

Cyanide binds to ferric iron in the blood and prevents electron transport at the cellular level. This also causes acidic blood levels as anaerobic respiration is used and lactic acid builds (Ganesan, Raza, & Vijayaraghavan, 2010). Clinical manifestations at lower severity levels include nausea and vomiting, blurred vision, shortness of breath, headache, and palpitations. At high concentrations, clinical manifestations include bright red skin, metabolic acidosis, rapid breathing followed by no breathing, loss of consciousness, and cardiac arrest (Chauhan et al., 2008).

Radiological Threats

Concern about unintentional radiological releases is often related to the nuclear power industry. Intentional releases might be in the form of a nuclear weapon or radiological dispersal device (RDD), which pose the same radiological threats as nuclear power accidents, though nuclear weapons and RDDs also pose an explosive hazard. This research will include the radiological hazard by considering RDDs.

Exposure to radiological hazards can occur through direct exposure, inhalation, and deposition. Direct exposure occurs through contact with the atmospheric plume of radioactive materials. Inhalation of radionuclides can occur from a plume or from ground-deposited material. Deposition allows radioactive materials to continue emitting radiation after the plume has passed, referred to as groundshine. Groundshine can cause significant long-term exposure hazards (EPA, 2013).

Ionizing radiation has sufficient energy to cause damage to cells. Ionizing radiation comes in several forms, including alpha, beta, gamma, x-ray, and neutron. Alpha particles are positively charged and comprised of two protons and two neutrons. They are relatively large and impart high energy levels over a short distance, which can cause significant damage to the DNA within cells by breaking DNA strands. Alpha particles are easily stopped by thin barriers, such as paper or the outer layer of skin, and only travel about three or four inches before interacting with matter. However, alpha particles can still cause damage if inhaled. Beta particles are negatively charged and made of electrons. They are somewhat smaller with lower energy and travel farther than alpha particles. Beta particles cause less direct damage, but can still break DNA strands. They can penetrate skin and travel up to about one hundred feet, but can be stopped by a layer of clothing, although direct contact with skin can cause beta burns. Gamma radiation consists of photons with no mass that travel at the speed of light. Gamma radiation has less potential to cause damage, but can penetrate almost anything with sufficient time. Several feet of concrete or several inches of lead are needed to stop gamma rays (Burke, 2003). Gamma radiation causes damage to cells indirectly by knocking apart water molecules, which creates free radicals that affect DNA in other cells (Woodruff et al., 2012). X-rays are not likely to be used in a RDD, but if encountered, they are similar to gamma radiation differing only in their point of origin. Neutrons are uncharged particles and result from splitting atoms, such as a nuclear reactor, accelerator, or detonation (Burke, 2003). Neutrons can cause whole body irradiation and react with nuclei in target cells, which can cause significant damage to the atomic structure (U.S. Department of the Army, 1996).

Cells have the ability to repair damaged DNA. However, certain types of damage, such as double strand breaks, are more likely to result in errors during the repair process, and repair takes time. Significant damage caused by sufficiently large doses of radiation can overwhelm the cell's repair mechanisms (Woodruff et al., 2012). When DNA is effectively changed by these mutations, cells can exhibit chromosomal abnormalities and deletions (Tubiana, Feinendegen, Yang, & Kaminski, 2009). This can lead to significant health problems over time, such as cancer and hereditary effects (Woodruff et al., 2012).

U.S. radiological standards use a linear no-threshold theory to model dose relationship to cancer (National Research Council, 2006). This assumes that cancer resulting from radiation exposure is a stochastic response, such that any dose, even a low dose, can cause cancer. Based on data suggesting a linear relationship at high doses, the theory assumes that any increase in dose increases the cancer risk linearly. However, several other theories model low dose response relationships differently and call the accuracy of the linear no-threshold (LNT) theory into question (Harbron, 2012; Pollycove & Feinendegen, 1999; Tubiana et al., 2009). The National Research Council's (2006) Biologic Effects of Ionizing Radiation VII report rejects these theories based on their review of the evidence.

There are several measures of radiation exposure. A curie is a unit used to measure the physical amount of radioactive material. A roentgen is a measure of the amount of ionization produced by a specific material. A rad or gray is a unit of measure for the dose absorbed by the specific tissue. Finally, a rem or sievert is used to measure the biological effect of the radiation dose on the target tissue (Burke, 2003; Mettler & Voelz, 2002). Fast-dividing cells, such as bone marrow, experience higher damage, because the cells don't have as much time to repair the DNA. The National Research Council (2006) estimates risks for various types of cancer in different demographics. For example, cancer risk depends on factors such as total dose, dose-rate of exposure, organ or tissue targeted, sex, age of exposure, and nationality, and there is considerable uncertainty in the estimates. For an overall approximate estimate of lifetime cancer risk from radiation exposure, the International Commission on Radiological Protection estimates that risk increases by 0.055 for every sievert of radiation (Wrixon, 2008).

Radiological hazards also have short-term effects. Acute radiation syndrome occurs at an effective dose of approximately 100 rem and has four phases: prodrome, latent, manifest illness, and recovery. The specific effects depend on dose. The prodrome phase occurs within the first 48-72 hours after exposure. Clinical manifestations include nausea/vomiting, diarrhea, dehydration, fever, and fatigue; the effects of nausea are generally not felt until a dosage exceeds 50 rem (NLM, 2015; Woodruff et al., 2012; Goans & Flynn, 2012). At a dose of 200-250 rem, everyone can expect to experience symptoms of illness, and some people will die within 30 days. A dose of 500 rem is considered fatal to half the exposed population within 30 days (Burke, 2003). The latent phase lasts for 1-2.5 weeks after the prodrome phase. Clinical manifestations are not prevalent, but leukocytes are decreasing. The manifest illness phase is obvious illness occurs after the latent period. Clinical manifestations depend on the specific organs damaged. The recovery phase can take weeks or months and, if the exposure was severe enough, may result in death (NLM, 2015; Woodruff et al., 2012; Goans & Flynn, 2012).

Incident Scene Management

Having considered technological and human-caused hazards, this section will consider response protocols. When emergency responders arrive on the scene of a CBRN incident, they will have to make various decisions and judgement calls on how best to manage the incident. Because of this, not every incident, even if the scenario was identical, will involve the same response. However, there are basic principles and procedures common to most incidents and response guidelines. This section will discuss some of those procedures, as well as a few factors that may affect a response effort.

Initial Phase of Response

While the specific response actions may vary, NATO (n.d.), EPA (1994), NLM (2015), OnGUARD (1996), Garcia, Rand, and Rinard (2011), Cashman (2008), and Lesak (1999) identify some factors important during the initial phase of response for most incidents. NATO defines the initial phase as the first 20 minutes of response. The DOT indicates that the initial phase lasts until technically qualified personnel, such as a HAZMAT response team, are available. The Emergency Response Guidebook (DOT et al., 2012) is designed to be used by first responders during this initial phase of response. Priorities during any incident include life-saving, protection of property, and protection of the environment. In this case, the incident must first be recognized as involving a CBRN hazard. Responders should gather information before and as they arrive on-scene, noting indicators of CBRN incidents and possible threats. Responders should look for any information that identifies the hazard (NATO, n.d.; NLM, 2015). This process of information gathering is sometimes referred to as size-up. Incident size-up is the process of evaluating visual indicators of the incident, using training and experience to interpret the information, and drawing conclusions to develop an action plan (Schnepp, 2010). The EPA (1994) recommends gathering information related to the date and time of release, risk to the surrounding public and property, terrain, weather, types of containers, and whether the release was into the air, water, or land. Air monitoring on and off site can also be used. As responders approach the scene to gather additional information, appropriate protective equipment should be worn (Garcia et al., 2011). Initial responders should also notify local authorities as soon as possible. Response personnel should continue gathering information and adjusting their response efforts as appropriate (NLM, 2015).

Next, NATO (n.d.) recommends that response efforts are focused on scene management to control the hazard. This includes establishing hazard zones, cordoning off contaminated areas, and managing/restricting traffic. As part of life-saving efforts, the inner cordon (similar to the initial isolation zone) should be evacuated and restricted to first responders wearing appropriate protective gear, and evacuation should be considered in the surrounding area. At this point, responders may decide to notify additional specialists for guidance on mitigating the CBRN hazard and collection and analysis of samples (NATO, n.d.).

Hazard Zone Control

Incident scene management is a complicated process involving many factors, so responders may use different strategies to establish hazard zones (Karasova, Abrahart, &

Jackson, 2007). Schnepp (2010) and Lesak (1999) recognize variation and flexibility in how control zones are established for different incidents and by different agencies and notes that most responders use a similar process, but may use different terminology. A common strategy is to define three control zones referred to as hot, warm, and cold zones (ATSDR, 2001; OnGUARD, 1996; Cashman, 2008). The hot zone is similar to the Emergency Response Guidebook's (ERG) initial isolation and protective action zones. The first zone is the hot zone, which immediately surrounds the hazard, is the most contaminated, and presents a danger to life or health. Only responders who need to be close to the hazard should enter the hot zone, and appropriate protective gear should be worn. The hot zone will vary in size based on the properties of the hazard. Various resources exist to aid in determining the size of the hot zone, such as plume modeling, atmospheric monitoring, and the ERG (DOT et al., 2012). Just outside the hot zone is the warm zone. The warm zone provides forward access and transition points for support personnel and equipment and includes the decontamination corridor. The cold zone is just outside the warm zone and establishes a safe area for the command post, various outside agencies, medical triage, media, and staging. The three zones commonly form concentric circles around the hazard (OnGUARD, 1996; Schnepp, 2010). Another common shape for the control zones is the keyhole, which consists of a circular region directly around the incident and an expanding wedge in the downwind direction (Goldblatt & Weinisch, 2005). While these cordon layouts are slightly different than the ERG, which is discussed later in this chapter, OnGUARD (1996) and Lesak (1999) still recommend that responders reference the ERG to determine appropriate distances for the specific hazard. However, Lesak also acknowledges that the ERG, plume models, and other similar references are guidelines and hazard distance determination is in some ways an art. Furthermore, hazard zones are likely to change as more information is gathered and as the situation or conditions change (Garcia et al., 2011).

Lesak (1999) identifies additional concepts for incident isolation and control. The incident perimeter designates the boundary past which only properly trained and protected personnel should enter. In addition to hot, warm, and cold zones, a fourth zone outside the incident perimeter is important to recognize, because personnel will pass from that zone to the inner zones. A circle is not always the best choice for the hot zone. Other shapes, such as keyhole, block, or teardrop shapes may be more appropriate, but the hot zone serves the same purpose regardless of shape. Lesak also describes subzones within each zone. For example, the hot zone includes the immediately dangerous to life and health (IDLH) line, which designates a subzone. Another consideration is that contaminants actually spread in three-dimensional space, so while cordons tend to be established along the ground, it may be appropriate to consider how far upwards the hazard could spread. This is especially true if multiple-story buildings are involved.

Garcia et al. (2011) recognize similar hot, warm, and cold zones, but recommend a unique shape for the cordons in an open area incident. The hot zone is an area immediately surrounding and downwind of the hazard release location. The hot zone slowly expands as the distance from the release increases. The warm zone is a crescent shape bordering the hot zone only on the upwind side. The cold zone exists outside both the hot and warm zones. The authors also recommend various minimum distances for the parameters of the zones, but do not provide the rationale behind those recommendations. They do acknowledge that distances are incident specific.

Cordons will be set up differently depending on the surrounding environment and infrastructure, as well. The specific location can impact the tactical decisions regarding where to set up cordons. For example, uphill and upwind may be in different directions from the release site, the site might be between large buildings, or the release could occur on a major highway in a downtown region (Lesak, 1999). When establishing isolation zones, a busy downtown area in a large city involves different issues than a rural area on a highway. The cordon should control access points near the incident site. For example, intersections, on ramps, and other traffic routes are logical choices for control points. Additionally, law enforcement may need to block or redirect traffic on nearby roads and intersections (Schnepp, 2010). Responders generally establish staging areas and command posts upwind of the hazard. However, if physical barriers such as highway sound barriers block access, the hot zone may need to expand to allow for a less than ideal staging location relative to the hazard. Wind direction can also affect where responders choose to delineate hazard zones. A shift in wind directions may require a change in cordons, or, if the incident occurs in an urban region, the effect of buildings on wind speed, direction, and stability can be significant (Lesak, 1999).

Responder Efficiency

Many factors can affect responder efficiency. The number of available responders with the appropriate knowledge and skills for a CBRN response is an important consideration. Similarly, fatigue and shift-work affect the availability of responders for the duration of the response. Equipment also affects responder efficiency. For a CBRN incident in particular, specialized equipment may be needed. Other resources can also be enabling during a response; for example, support organizations like the DOT and mutual aid agreements can provide additional support that improves efficiency. A critical factor for many incidents is the quality of emergency operations plans or other checklists. The specific location and time of day can also influence efficiency. Remote areas may require less personnel but be harder to access. During rush hour, responders and evacuation efforts might be hampered by the additional traffic congestion. During winter, snow and ice conditions may slow response transit times (EPA, 1994). In general, more hazard zone control points or cordons increase logistical challenges, because those cordons must be established and maintained (Lesak, 1999).

Shadow Evacuation

Shadow evacuation can be a complicating issue during an incident response. When individuals become aware of a hazardous incident, they interpret their risk based on the information available to them and their personal perception of vulnerability (Dash & Gladwin, 2007). Sometimes, people who are outside the hazard area will choose to self-evacuate to a location farther from the hazard. This is known as shadow evacuation, because the region of shadow evacuees tends to be around the mandatory, and if applicable voluntary, evacuation zones. Extra evacuees add burden to the evacuation traffic process (Goldblatt & Weinisch (2005). In some cases, one area might be directed to evacuate, another to shelter-in-place, and another to take no protective action. People from any area may choose to self-evacuate, even if that action actually exposes them to more risk (Sorenson, 2004). Similar to shadow evacuation, expanding hazard zones may result in additional evacuation-related risks.

Creeping Conservatism

During a response, various agencies may be involved in decisions about safety levels or protective actions. Sometimes, each agency will select the more conservative option, round up, or add a slight factor of safety. This phenomenon is referred to as creeping conservatism (Lindell, 2000). For most CBRN incidents, reality dictates deviations from the simple shapes of published hazard zone guidelines. When responders add distance to the published hazard distances, such as by expanding the zones to the nearest physical boundaries, they are effectively practicing creeping conservatism.

Protective Actions

Many researchers have investigated the relative merits of sheltering versus evacuation in the wake of a CBRN incident. The decision is complex and can depend on many potential factors, such as available shelter, population density, weather conditions, and traffic (Sorenson, 2004; Chakrabarti & Parikh, 2013). Most researchers have found that sheltering-in-place is more effective in minimizing casualties than evacuating in the initial time frame after an outside CBRN incident, assuming that adequate shelter is available (Dillon, 2014). However, there is not a clear consensus on the optimal timing for sheltering or evacuating, and specific recommendations vary based on availability of shelters, traffic networks, and the location of nearby population centers. In most CBRN releases, there is little to no advance warning to the nearby population, so there is insufficient time to evacuate before the contaminants arrive. There are additional hazards associated with evacuation, especially if the release involved an explosion. For example, people are directly exposed to the contaminant while outside, there may be debris in the evacuation path, traffic may become significantly congested, and debris may prevent or slow vehicle traffic.

In the case of a 10 kiloton improvised nuclear device detonated in Washington DC, Wein (2010) recommends sheltering in place underground for at least 12 hours to minimize the number of deaths, although various factors influence the optimal strategy, such as pedestrian traffic, availability of above and below ground shelters, self-evacuation compared to directed evacuation, and availability of medical care. To minimize radiation exposure, Dillon (2014) determined that the optimal shelter time is proportional to the dose rate. He suggests immediately transiting from inadequate to adequate shelter if the distance can be travelled in about five minutes, but waiting to transit if the adequate shelter is farther.

Exposure Guidelines

Various agencies have developed guidelines for airborne concentration thresholds above which certain health effects can be expected. Three exposure guidelines frequently used in the U.S. include acute exposure guideline levels (AEGLs), emergency response planning guidelines (ERPGs), and temporary emergency exposure limits (TEELs). Additionally, immediately dangerous to life and health (IDLH) levels are sometimes used for worker-specific protection guidelines or in the absence of the previous three guidelines. Protective Action Guides (PAGs) are frequently used for radiological exposures. The relevant exposure guidelines for this study's selected hazards are shown in Table 1.

Acute Exposure Guideline Levels

AEGLs are developed using a rigorous methodology. Originally, the National Research Council (NRC) developed AEGLs through the National Advisory Committee for Acute Exposure Guideline Levels for Hazardous Substances. Since 2011, the National Academies of Science has taken responsibility for finalizing interim AEGLs that were developed by the NRC (EPA, 2015). AEGLs account for the entire population, including those more sensitive to airborne contaminants. AEGLs are developed at three severity levels for five different time increments ranging from ten minutes to eight hours. The lowest level, AEGL-1 designates the concentration above which the general population can expect to experience irritation and other non-disabling, temporary health effects. AEGL-2 designates the concentration above which the general population can expect to experience serious, long-lasting health effects or impaired ability to implement the appropriate protective actions, such as evacuation or shelter-in-place. AEGL-3 designates the concentration above which the general population can expect to experience life-threatening effects or death (Brown, Freeman, & Haney, 2013).

Emergency Response Planning Guidelines

The American Industrial Hygiene Association developed ERPGs using data from human and animal studies. ERPGs include three levels of severity all at a duration of one hour. ERPGs account for the general population and do not include sensitive individuals. They do not include a factor of safety, and it is recommended that they not be extrapolated to longer time durations of exposure (O'Mahony et al., 2008). The levels of severity are similar to those for AEGLs. ERPG-1 designates the concentration below which most individuals can expect to experience nothing more than mild temporary health effects. ERPG-2 designates the concentration below which most individuals can expect to not experience any long-lasting or serious health effects or an impaired ability to implement appropriate protective actions. ERPG-3 designates the concentration below which most individuals can be exposed without life-threatening health effects (Brown, Freeman, & Haney, 2013). Table 1 shows that the ERPG-2 concentrations are similar to the AEGL-2 concentrations for four of the five chemical hazards of interest. The ERPG-2 value is twice as high as the AEGL-2 value for sulfur dioxide.

Temporary Emergency Exposure Limits

The U.S. Department of Energy developed TEELs for chemicals that do not have ERPGs. TEELs are approximations rather than estimations based on experimental data from studies, as the ERPGs are, but they do follow a standard methodology. They do not include a factor of safety and are developed for three levels of severity (O'Mahony et al., 2008). TEEL-2 concentrations are defined the same way as ERPG-2 values, but TEEL-2 values use exposure durations of only 15 minutes. TEELs have been developed for over 3,000 chemicals (Brown, Freeman, & Haney, 2013).

Immediately Dangerous to Life and Health

The National Institute for Occupational Safety and Health (NIOSH) developed IDLH values to designate where workers should use respirator protection. An IDLH condition is defined as a condition that "poses a threat of exposure to airborne contaminants when that exposure is likely to cause death or immediate or delayed permanent adverse health effects or prevent escape from such an environment" (NIOSH, 1994). IDLH values are generally higher than ERPG-2 or AEGL-2 values, because IDLH is designed for a healthy adult population exposed for a duration of only 30 minutes (Brown, Freeman, & Haney, 2013). As shown in Table 1, the IDLH values are considerably larger than the corresponding AEGL-2 and ERPG-2 values.

Protective Action Guides

First developed in the 1960s, the EPA (2013) defines a PAG as "the projected dose to an individual from a release of radioactive material at which a specific protective action to reduce or avoid that dose is recommended." PAGs are developed following three principles: prevention of acute effects, balance between protection and other factors such that benefits outweigh harm, and reduction of chronic effects risk. During the early phase of an incident, usually lasting hours to days, the recommended PAG is one to five rem over four days. This means that if the projected dose to the whole body exceeds one to five rem over four days, then evacuation or shelter-in-place should be implemented. The projected dose is affected by factors such as duration of the plume, rate of release, terrain, physical properties of the particles, wind speed, and air turbulence. The EPA (2013) publishes a PAG Manual that includes guidance on how to calculate projected doses.

Table 1: Exposure Guidelines (NOAA, 2016; CDC, 2015; NIOSH, 2011; EPA, 2013)

	Anhydrous Ammonia	**Chlorine**	**Sulfur Dioxide**	**VX**	**Sarin**	**RDD**
AEGL-2 (60 min)	160 ppm	2 ppm	0.75 ppm	0.00027 ppm	0.006 ppm	--
ERPG-2 (60 min)	150 ppm	3 ppm	3 ppm	--	--	--
IDLH (30 min)	300 ppm	10 ppm	100 ppm	0.003 mg/m^3	0.1 mg/m^3	--
PAG	--	--	--	--	--	1-5 rem/ 4 days

Hazard Distance Determination

Several factors affect the appropriate distances to use for CBRN hazard zones. In the early stages of response, this is accomplished by selecting the basic conditions in the ERG and setting up cordons at the corresponding initial isolation and protective action distances. In later stages of response, additional information will allow responders to adjust the cordons to be more accurate. For example, responders can use plume modeling software to refine the theoretical extent of the airborne contamination and sampling procedures to refine the actual extent of the ground truth. Both early and later methods rely on similar basic information, such as type of chemical, size of release, time of day, wind direction, and wind speeds. Later methods may include more details in those categories, as well as additional information.

Different chemicals or classes of chemicals have different physical properties, which leads to different hazard distances. For example, dense chemical gases that are heavier than air tend to sink, engage in less vertical mixing, and disperse into the atmosphere more slowly than neutrally buoyant gases (Brown, Freeman, & Haney, 2013). Volatile chemicals tend to evaporate and thus dissipate more quickly, but also spread out over a greater distance than nonvolatile liquids.

The volume of the release has obvious implications for the extent of the contamination. Larger releases result in larger required hazard distances.

Brown, Freeman, and Haney (2013) explain how time of day significantly affects the chemical's passive dispersion in the atmosphere. Typically, air temperature lowers as altitude increases; temperature inversion is the opposite scenario where a band of warmer air is above colder air. This warmer air acts as a sort of cap, such that the rising air cannot continue to rise. This causes a convective boundary layer from the surface of the earth to the lowest temperature inversion, and the atmosphere tends to be unstable and turbulent. During the day, the sun warms the earth's surface, which warms the air directly above the surface. This warmer air rises and cools until the lowest temperature inversion is encountered, which may be fairly large. This vertical air movement contributes to a more rapid dispersion of chemical contaminants. During the night, the earth's heat escapes to space, and the air closest to the earth's surfaces cools the fastest. This forms a stratified boundary layer that is more stable and less turbulent. The reduction in energy contributes to a lower, thin layer close to the earth's surface. This results in less air mixing and vertical dispersion of contaminants. Because of this behavior, daytime spills require smaller hazard distances than nighttime spills. The difference between a daytime spill with no cloud cover and a nighttime spill with no cloud cover can be as much as three orders of magnitude.

Wind direction doesn't contribute to the size of the hazard distances, but rather the direction of the protective action zone. As expected, airborne hazards tend to spread in the direction of the wind. However, wind speed does affect hazard distances. Higher wind speeds result in more air mixing and faster dispersion into the atmosphere, so smaller distances are required. Lower wind speeds are more stable and slowly spread out from the spill location, requiring larger distances.

Standard Hazard Zone Distances

Currently, the Emergency Response Guidebook (ERG) is the primary reference for responders in North America to determine appropriate cordon distances for hazardous material releases during the initial phase of the incident, and many emergency response resources direct readers to the ERG for initial incident information (NLM, 2015; Schnepp, 2010; Cashman, 2008; OnGUARD, 1996; Lesak, 1999). Produced by the U.S. DOT, Transport Canada, and Secretariat of Communications and Transportation of Mexico, it is specifically intended for transportation incidents. While there may limited use for the ERG during a fixed facility incident, the recommended hazard distances were determined using transportation scenarios (Brown, Freeman, & Haney, 2013). For a fixed facility incident, the Emergency Planning and Community Right-to-Know Act (1986) mandates that communities plan for incidents at facilities that use or store hazardous chemicals. These plans include evacuation plans and the identification of populations and areas likely to be impacted by an incident. Additionally, facilities are required to maintain specific chemical information in material safety data sheets and to make this information available to emergency response agencies and the public. This research focuses on transportation incidents.

The ERG contains four sections. The first two sections can be used to identify the material and its guide number. The third section provides guidelines for each guide number that explain potential hazards and appropriate response actions. The final section establishes guidelines for the initial isolation and protective action distances. This fourth section provides information for small and large spills and day and night conditions. It also provides additional details for a selected set of hazardous inhalation materials that comprise the majority of transportation related spills. The initial isolation zone is a circular region directly around the incident site. Within the initial isolation zone, life-threatening conditions can occur downwind of the release and dangerous conditions can occur upwind due to wind direction variation. The protective action zone is a square area in the downwind wind direction where protective actions, such as evacuation or shelter-in-place, should be initiated for the general population. The geometry used to establish the initial isolation and protective action zones is shown in Figure 1.

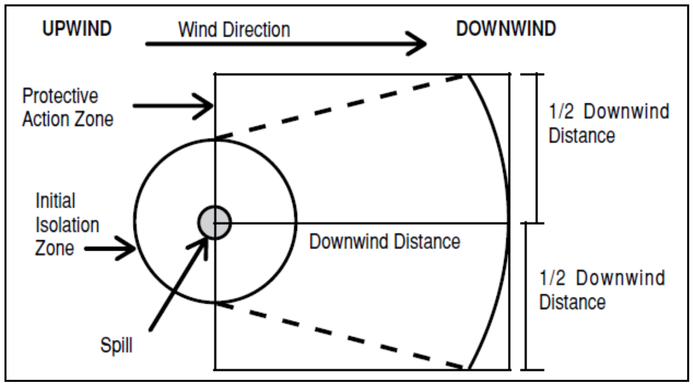

Figure 1: ERG's Initial Isolation and Protective Action Zones (DOT et al., 2012)

The DOT determined the protective action distances for each material using a statistical analysis of release amounts and rates, downwind dispersion, and toxicological exposure guidelines. Thousands of possible releases were modeled for each chemical using data generated from dispersion models, meteorological observations, and the Hazardous Materials Information System database. To account for the likely differences between chemicals used as a weapon and accidental spills, such as a greater proportion of releases in an urban area for deliberate releases, different release scenarios were generated in the analysis. Distances were defined by health criteria using final AEGL-2 levels, ERPG-2 levels, interim AEGL-2 levels, or animal studies and expert opinion, in that order of priority. Final AEGL values were used for the three TIC/TIMs and two chemical warfare agents studied in this research. The 90^{th} percentile distances of the resulting distributions are reported as protective action distances in the ERG. The initial isolation distances are determined by selecting the smaller of two values: the distance corresponding with the one-hour LC_{50} concentration level or 15% of the protective action distance during the day for gases and 7.5% of the protective action distance during the day for liquids (Brown, Freeman, & Haney, 2013). The LC_{50} value is the lethal concentration at which 50% of the exposed population is expected to die.

For the purposes of this research, a large TIC/TIM spill (more than 55 U.S. gallons) involving a highway tank truck or trailer in moderate winds (between 6 and 12 miles per hour) during the day was selected for study. For the chemical warfare agents VX and GB, a large release (4.4 to 55 pounds) during the day was selected. The reasoning behind the selected conditions is discussed further in Chapter 3. The relevant distances are shown in Table 2 (DOT et al., 2012).

Table 2: ERG Hazard Distances

Hazard	Initial Isolation Distance	Protective Action Distance
Ammonia, Anhydrous	125 m / 400 ft	500 m / 0.3 miles
Chlorine	1,000 m / 3,000 ft	3,500 m / 2.2 miles
Sulfur Dioxide	1,000 m / 3,000 ft	7,600 m / 4.7 miles
VX (used as a weapon)	60 m / 200 ft	400 m / 0.2 miles
GB, Sarin (used as a weapon)	400 m / 1,250 ft	2,100 m / 1.3 miles

Musolino et al. (2013) provides guidelines for RDD hazard zones based on over 1,000 experiments conducted at the Sandia National Laboratories for more than 25 years. They used the data from these experiments to determine the most probable hazard boundaries for an initial response when no information about the material or geometry is known, setting the initial hot zone at 250 meters. The hot zone is similar to the initial isolation zone and designates the area restricted to emergency responders in appropriate protective gear. Between a 250 meter radius and a 500 meter radius and within 2,000 meters in the downwind direction, people should remain in or seek out an intact building to shelter in until directed to evacuate. Once measurements are made and more information is known, the use of National Council of Radiation Protection and Measurements (NCRP) boundaries is recommended. Musolino's recommendations are shown in Table 3, and the layout of the recommended zones is shown in Figure 2.

Table 3: Musolino RDD Hazard Distances

Hazard	Initial Hot Zone	Sheltering Zone
Radiological Dispersal Device	250 m	500 m radius and 2,000 m downwind

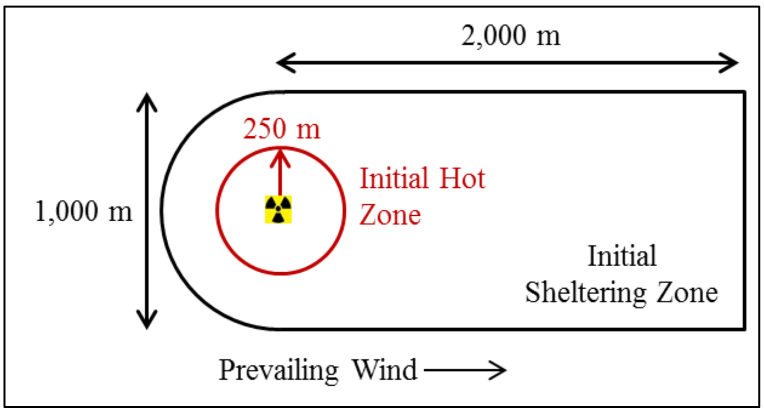

Figure 2: RDD Recommended Hazard Zones (adapted from Musolino et al., 2013)

Summary

This chapter reviewed the relevant literature concerning technological and human-caused hazards and their effects, typical incident response management protocols, factors affecting the decision to evacuate or shelter-in-place, exposure guidelines, and standard hazard zone determinations and recommendations. Three technological and three human-caused hazards were selected for use in this study, as they provide a range of possible incidents, chemical properties, and physiological effects. Incident response management is a complex process involving a plethora of factors, including incident commander judgement and experience, that influence the specific procedures implemented, although there are commonalities in CBRN incident management and hazard zone implementation. Responders typically direct either evacuation or shelter-in-place for the population within the hazard zones; this is also a complex decision incorporating many variables. Hazard zone recommendations generally rely on exposure guidelines that connect physiological effects to protective actions. In the United States, the Emergency Response Guidebook (DOT et al., 2012) is used by most emergency responders to determine initial isolation and protective action distances for hundreds of chemicals, and Musolino et al.'s (2013) recommendation is widely used to determine isolation and sheltering zones for radiological dispersal device incidents.

III. Methodology

Chapter Overview

Managing CBRN incidents is a complex process involving many steps. An important step in the initial phase of response is the set-up of hazard zones. In the U.S. and in this research, the Emergency Response Guidebook (DOT, 2012) and Musolino et al. (2013) is referenced to determine standard hazard distances and zones for chemical and radiological releases, respectively. The methodology for this research was developed to answer the three research questions:

1. How do published emergency hazard zones for various CBRNE incidents change when adapted to physical boundaries?

2. What effects do different environments and locations have on emergency hazard zones when the zones are adapted to physical boundaries?

3. Is there a preferred set of physical boundaries that improves responder efficiency?

These questions were answered by developing a program to use with ESRI's ArcGIS® 10.2 software (2014). This research lends itself to geospatial analysis, because the research seeks to describe the relationship between hazard zones with particular dimensions, surrounding physical boundaries, areal calculations, and residential population estimates. The input data of road, railroad, and river networks and population counts are geospatial data, because they inherently include geographic locations. A geographic information system (GIS) enables geospatial analysis, which incorporates data's geographic location into a statistical analysis.

To understand the changes in CBRN hazard zones when adapted to physical boundaries, data were collected and multiple analyses were conducted. The methodology consisted of three main stages. First, locations for the CBRN incidents were selected, and GIS data was obtained. Second, a simulation was developed in ArcGIS® 10.2 to automate the construction of hazard zones, calculation of the affected population and area for each zone, and counting of the number of intersections in the cordon boundaries. Finally, the data collected from the simulations were analyzed using statistical comparisons.

Location Selection

Three main locations were selected for this research by analyzing U.S. Department of Transportation data from 1 January 2010 through 10 July 2015. The data includes reported accidental chemical release incidents in the United States. Incident totals were sorted by city to determine where the highest incident rates occurred. Additionally, because relatively non-hazardous paint spills (UN1263) accounted for a large number of incidents (17,055 out of 78,512), paint spills were removed and the dataset reanalyzed. The data were also considered by looking at transportation incidents rather than the combined fixed facility and transportation incidents. The cities with the highest number of incidents are shown in Table 4.

Table 4: U.S. Chemical Release Incidents (2010-2015)

	Total Incidents		Total (without paint)		Transit (without paint)	
1	Houston, TX	1319	Hodgkins, IL	1195	Hodgkins, IL	1012
2	Hodgkins, IL	1269	Houston, TX	974	Addison, IL	384
3	Jacksonville, FL	795	Columbus, OH	634	Columbus, OH	321
4	Salt Lake City, UT	786	Jacksonville, FL	621	Houston, TX	302
5	Portland, OR	766	Salt Lake City, UT	580	Commerce City, CO	261
6	Memphis, TN	764	Portland, OR	560	Jacksonville, FL	256
7	Dallas, TX	734	Commerce City, CO	557	Bloomington, CA	192
8	Columbus, OH	728	Memphis, TN	557	Earth City, MO	154
9	Indianapolis, IN	684	Dallas, TX	510	Dallas, TX	151
10	Phoenix, AZ	634	Indianapolis, IN	493	Ellenwood, GA	145

Additionally, the data were analyzed for the three TIC/TIM chemicals of interest: anhydrous ammonia, chlorine, and sulfur dioxide. Because these selections resulted in less data, the date range was expanded to include 20 years from 1995 to 2015. The results were primarily used to verify that those chemicals could be present in those locations rather than rank ordering the cities.

Chicago, Houston, and Denver were selected for analysis. Hodgkins and Addison are suburbs of Chicago, Beaumont is a suburb of Houston, and Commerce City is a suburb of Denver. The GIS data for these locations were downloaded from the U.S. Census Bureau's TIGER/Line (U.S. Census Bureau, 2015) website by state. The data consisted of shapefiles pre-joined to 2010 census block population counts. The GIS data with roads, railroads, and waterways were downloaded from the Census Bureau and the U.S. Geological Survey's National Map Viewer (U.S. Geological Survey (USGS), 2015).

These locations may not represent the top three most likely locations for a chemical incident to occur. However, they still represent areas where chemical incidents have a high likelihood of occurrence and serve as case study areas for this research. To capture a wider range of location types, three locations were selected near each metropolitan area: downtown/urban, suburban, and rural just outside the city. Additionally, Houston and Chicago represent plains terrain, whereas Denver represents mountainous terrain.

Research Simulation

A model was developed in ArcGIS® to standardize and automate the creation of hazard zones, calculation of population and area affected by the zones, and counting of intersections in the new hazard zone boundaries.

Initial Conditions

Initial conditions for the incidents were determined to be the same or similar for each hazard scenario. The ERG (2012) lists hazard distances for large and small spills, day and night conditions, and wind speeds. Large spills are defined as more than 55 gallons (between 4.4 and 55 pounds for certain chemical warfare agents, including VX and GB). Day is defined as between sunrise and sunset. High wind is defined as more than 12 mph, moderate wind is 6-12 mph, and low wind is less than 6 mph. Container types include rail tank car, highway tank truck or trailer, agricultural nurse tank (for anhydrous ammonia), multiple ton cylinders, and multiple small cylinders or single ton cylinder. Wind speeds and container types are only differentiated for large spills of the six common TIHs; all other hazards don't consider these differences.

Wind direction was selected using the prevailing wind direction for that location. The prevailing wind direction was defined as the wind direction that occurred most frequently over all months of the year. In Houston, the prevailing winds are from the southeast (Texas Commission on Environmental Quality, 2015), and the average wind speed is 9.02 mph (National Water and Climate Center, 2002). In Chicago, the prevailing winds are from the southwest, and the average wind speed is about 10.6 mph (Wendland, 1981; Illinois State Climatologist Office, 2004). In Denver, the prevailing winds are from the south, and the average wind speed is 10.0 mph (Western Regional Climate Center, 2002 & 2008). Each of these wind speeds falls within the moderate wind category in the ERG.

Large spills involving highway tank trucks or trailers during the day in moderate winds were selected as initial conditions. Using large spills provides for a more conservative approach than small spills. Highway trucks are commonly used for hazardous materials transport, could reasonably be used in an intentional release, and are prevalent throughout the U.S. anywhere that roads exist. Daytime is a more likely condition for an intentional release, and more people are likely to be outside and impacted by the incident. Moderate winds were selected, because average annual wind speeds fall within the moderate category in each city. Changing any of these initial conditions could result in different standard hazard distances. For example, small spills have smaller hazard distances, rail tank car accidents have larger hazard distances, and night conditions have larger hazard distances.

These initial conditions were used as inputs to determine the standard hazard zones based on ERG (DOT et al., 2012) and Musolino's (2013) guidance. The dimensions of the standard hazard zones were then created in ArcMap™ in the three cities of interest. Three initial maps (one for each metropolitan area) were created using data from TIGER/Line data from the U.S. Census Bureau and USGS data. The maps consisted of roads, railroads, rivers, and census block data across the entire metropolitan area. The maps were then further subdivided into downtown, suburban, and rural regions (see Figure 3). Using a random number generator, specific hazard impact locations were chosen. The specific hazards and release locations were used to calculate the growth of hazard zones by using physical boundaries.

ArcGIS® Model

The hazard zones were expanded to the nearest physical boundaries, which are defined as roads, railroads, and rivers. Hazard zones were expanded to go around any boundaries that the original cordons intersected. Additionally, they were expanded to the nearest boundary. By design, hazard zones were not allowed to shrink in size, so matching physical boundaries resulted in equal or larger areas. This choice ensured that the new hazard zones did not assume any additional risk to the population.

ArcGIS® was used to calculate the area and population enclosed by each cordon for each case. The model loops through each hazard type and each random point location to generate and compile data for each metropolitan area. Additionally, the model counts the number of intersections in each new hazard zone cordon to describe responder efficiency. From a practical standpoint, roads are likely to be used in setting up hazard cordons anywhere that roads exist. Therefore, roads are included in every boundary set. Requiring roads to be included in every set results in four combinations of boundaries: roads only, roads and railroads, roads and rivers, and all three. To compare efficiency among different sets of physical boundaries, the new hazard zones are generated four times – once for each combination of physical boundaries. The complete python scripts are included in Appendix A. The general algorithm is outlined below. A chlorine spill located in suburban Denver was used to illustrate the process. Each map uses the Canada Albers Equal Area Conic projected coordinate system with the North American 1983 datum and central meridian of -96.0.

Python Model Algorithm

1. Initialization:
    a. Set up physical boundary files with a separate python script (this was accomplished only once per city).
        i. Ensure a consistent projection that preserves areas.
        ii. Clip roads, railroads, rivers, and census blocks to relevant areas in order to reduce the size of the geodatabase file and improve processing time.
        iii. Create shapefiles for physical boundaries: Roads; Merge roads and railroads; Merge roads and rivers; and Merge roads, railroads, and rivers to create four shapefiles.
        iv. Break all roads, railroads, and rivers into line segments at every intersection, so that every boundary can be used and to identify intersections that will later be counted.
    b. Define inputs of wind direction, spill regions, city name, and number of random points to be generated within each region.
    c. Define program variables that are in the geodatabase file or will be created and saved in the geodatabase file.
    d. Delete old versions of layers and tables.

e. Assign standard hazard distances based on hazard using the ERG (2012) and Musolino et al. (2013) recommendations.

f. Generate random points within each of three regions and add XY coordinate data for each point.

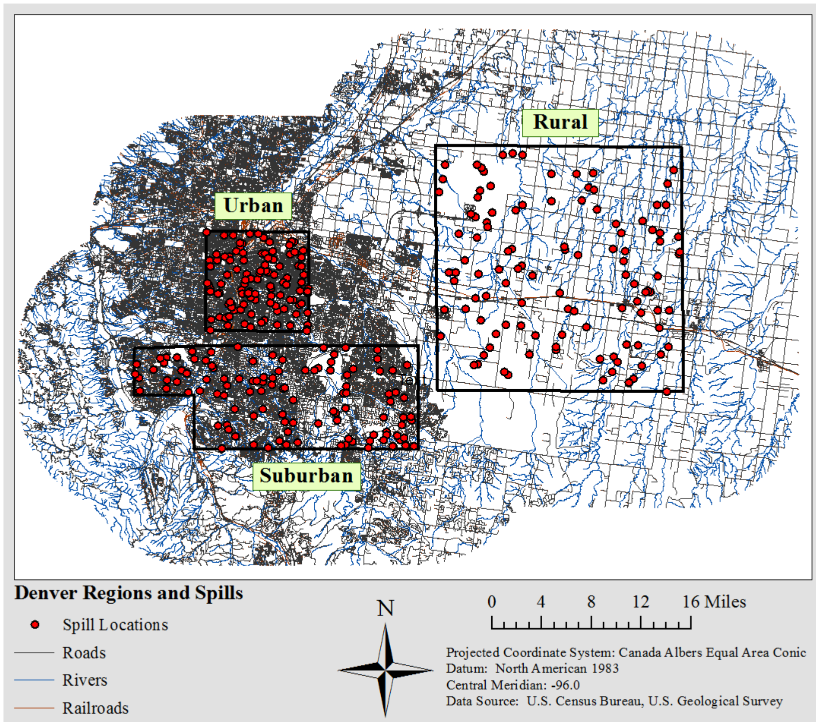

Figure 3: Denver regions and random spills (Steps 1a-f)

g. Add field in census block attribute table to store original shape areas for each census block.

h. Create an empty table to store statistics with all relevant fields. This table will contain the data used to answer the research questions in Chapter IV.

Table 5: Statistics Table Attributes and Descriptions (Step 1h)

OBJECTID	Unique identifier used by ArcGIS®
Frequency	Number of census blocks affected
Sum_Pop_Affected	Total population affected by the zone
SUM_Area_Affected	Total area affected by the zone (square meters)
Hazard	Number 0-5 identifying hazard
Zone	Initial Isolation or Protective Action
Std_New	Standard or New zones
Environment	Urban, Suburban, or Rural
City	Chicago, Denver, or Houston
Point_num	Spill location point number
Vertices	Number of intersections
Boundary_Set	NA = standard zones do not use boundaries, R = roads, RRail = roads and railroads, RRiver = roads and rivers, RRR = all three
Pop_diff	Population difference between standard and new zones
Area_diff	Area difference between standard and new zones
Pop_diff_per	Percent difference in population between standard and new zones
Area_diff_per	Percent difference in area between standard and new zones

2. Calculate Standard Initial Isolation Zone:

    a. Select the first (or next) spill location point and hazard.

    b. Create a buffer based on hazard distances around the selected spill location point for the initial isolation zone, using the information from step 1e.

    c. Clip census block data by the initial isolation zone buffer to determine the number of people affected.

    d. Calculate population and area affected and count intersections:

        i. Add population and area fields in attribute table of clipped data

        ii. Calculate affected areas of each census block in square meters

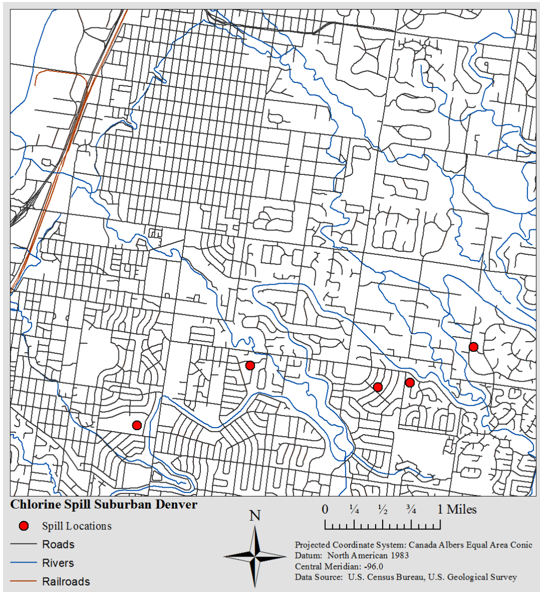

Figure 4: Chlorine spill in suburban Denver

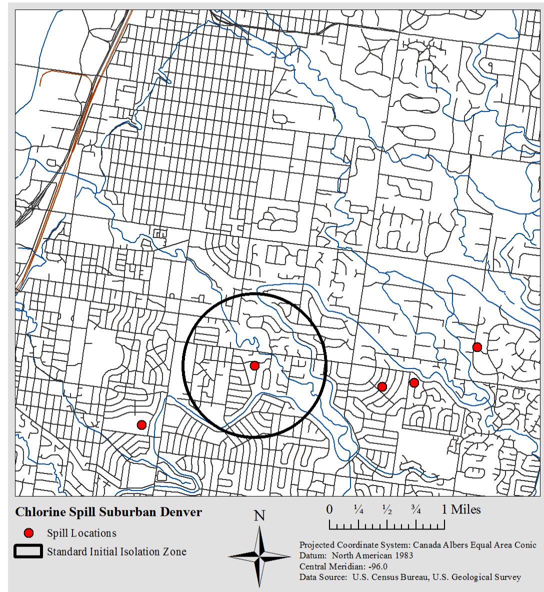

Figure 5: Initial isolation zone (Step 2b)

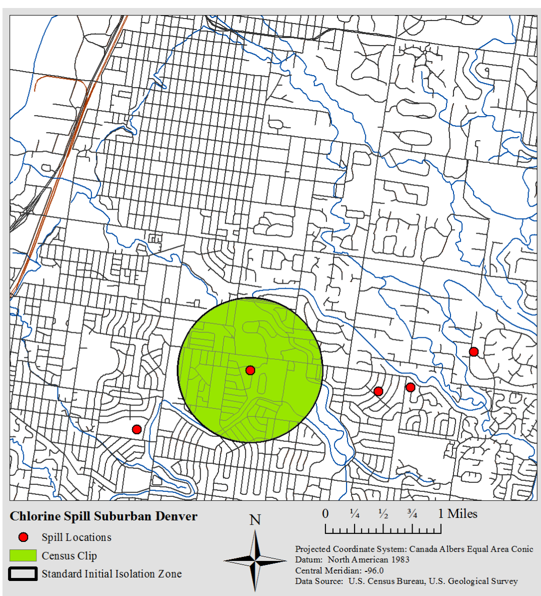

Figure 6: Census blocks clipped (Step 2c)

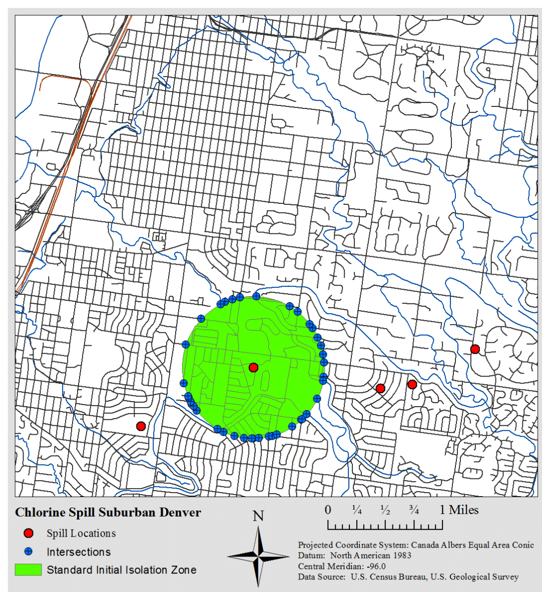

Figure 7: Intersections (Step 2dv)

iii. Calculate affected populations using census data, and calculate proportions of populations in blocks that are intersected by the initial isolation zone.

iv. Sum populations and areas for the entire initial isolation zone.

v. Count the intersections of the zone with nearby boundaries.

e. Add statistics to statistics table

3. Calculate Standard Protective Action Zone:

a. Read the XY coordinates for the spill location from step 2a.

b. Calculate the coordinates of corners of the protective action zone given the spill location coordinates, and rotate according to the wind direction.

c. Create a rectangle from the corner coordinates to establish the extent of the protective action zone.

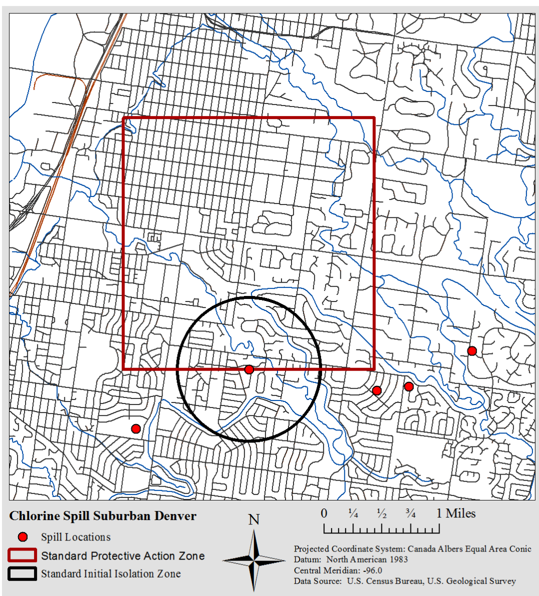

Figure 8: Standard downwind zone (Step 3c)

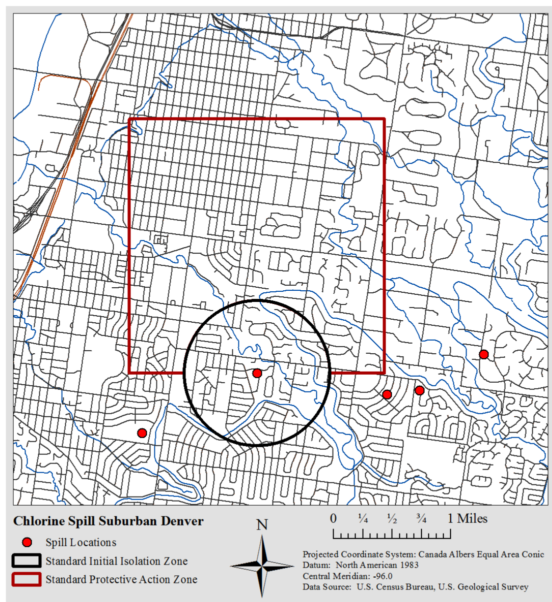

Figure 9: Zones without overlap (Step 3d)

d. Subtract from the protective action zone the area that intersects the initial isolation zone, so that areas and population are not double counted.

e. Clip the census block data by protective action zone to determine the number of people affected.

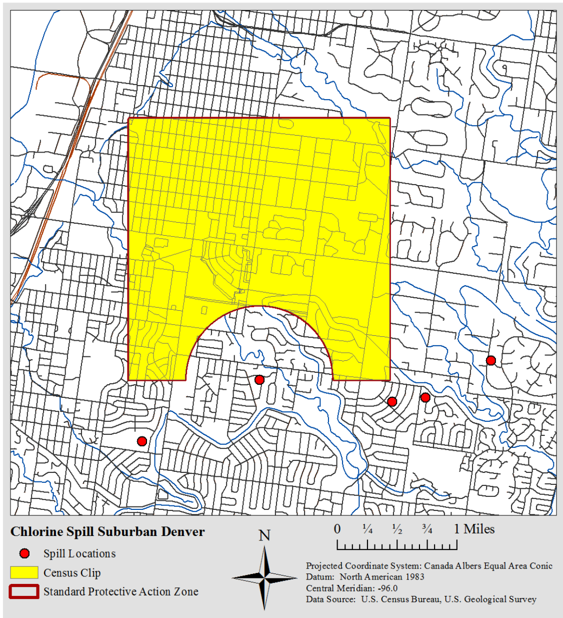

Figure 10: Census data clipped to protective action zone (Step 3e)

f. Compile statistics for population and area affected using the same process as step 2d for the protective action zone.

g. Add the total number of intersections in the initial isolation and protective action zones, and record the sum in the statistics table. As shown in Table 6, the area and population affected by the standard hazard zones, as well as the number of intersections (labeled "Vertices") have been added. However, the statistics that will be used to answer the research questions (labeled Pop_diff, Area_diff, Pop_diff_per, and Area_diff_per) have not yet been calculated; placeholders or null values are put in those columns in the table.

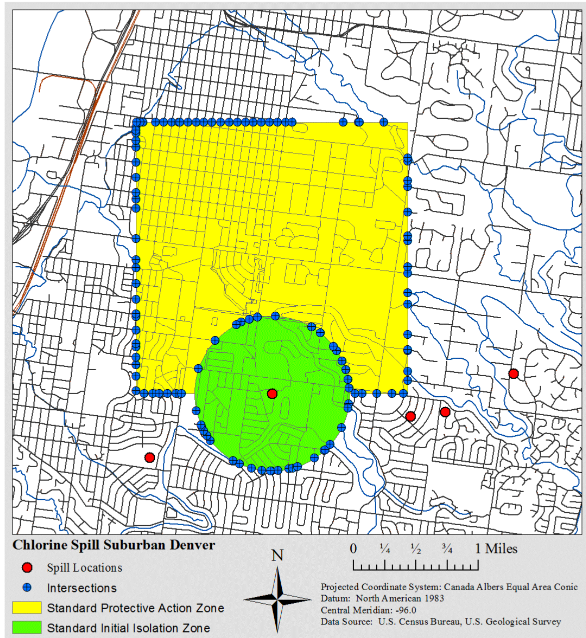

Figure 11: Standard hazard zone intersections (Step 3g)

Table 6: Statistics Table with Standard Hazard Zones Data (Steps 3f-g)

OBJ	FREQ	SUM_Pop_Aff	SUM_Area_Aff	Hazard	Zone	Std_New	Envir	City	Point	Vertices	Boundar	Pop_diff	Area_diff	Pop_diff_per	Area_diff_per
1	86	3239.440021	3141590.064636	1	Initial Isolation	Standard	2	Denver	67	39	NA	-1	-1	<Null>	<Null>
2	326	15102.111448	10679206.13343	1	Protective Action	Standard	2	Denver	67	115	NA	-1	-1	<Null>	<Null>

At the conclusion of Step 3, the standard initial isolation and protective action zones have been generated, the populations and areas affected by each have been calculated, and the total number of intersections in the cordons has been counted. This is the baseline that the new zones will be compared against.

4. Calculate New Initial Isolation Zone (matched to physical boundaries):
    a. Select lines of interest that will be used to draw the new hazard zone.
        i. Select all lines within a sufficient buffer distance of the standard initial isolation zone.
        ii. Remove from selection the lines that cross the boundary of the standard initial isolation zone.

iii. Remove from selection the lines that are within the initial isolation zone.

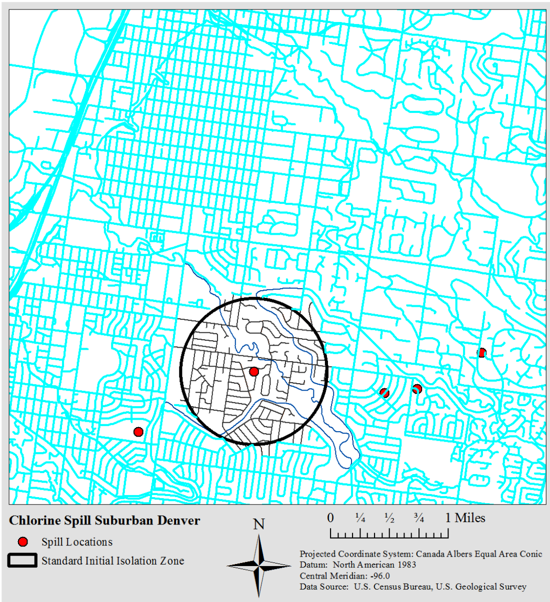

Figure 12: Lines selected around zone (Step 4a)

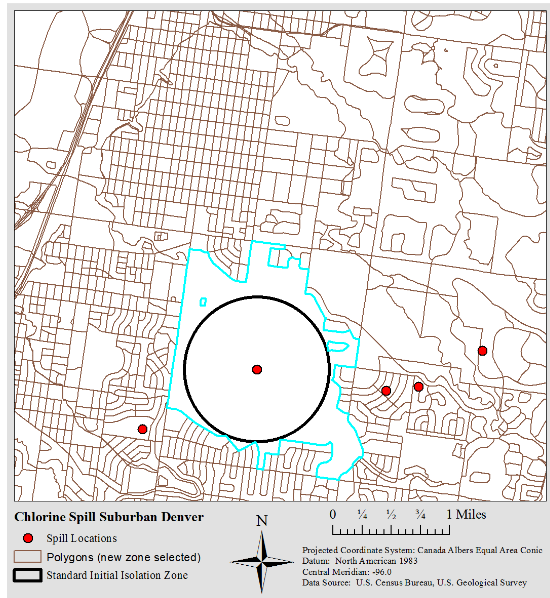

Figure 13: Lines selected for new zone (Step 4c)

b. Turn selected lines into polygons.

c. Select the polygon that contains the initial isolation zone – this is the expansion of the initial isolation zone to the nearest physical boundaries.

d. Ensure the polygon (new isolation zone) does not contain holes. Figure 13 illustrates that some polygons have holes completely within the polygon if a smaller polygon between the standard zone and expanded zone can be created using roads, railroads, and rivers. Eliminating any such holes ensures no areas are marked as "safe" if they are within a larger hazard area.

e. Clip census block data by the new initial isolation zone to determine population affected.

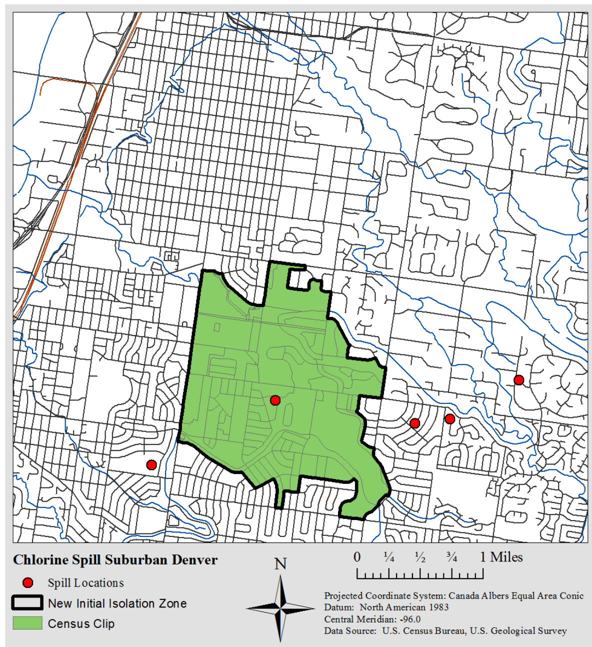

Figure 14: Census data clipped to new initial isolation zone (Step 4e)

f. Compile statistics for population and area affected using the same process as step 2d for the new initial isolation zone.

5. Calculate New Protective Action Zone:

    a. Select lines of interest using the same process as step 4a for the new protective action zone.

    b. Turn the selected lines into polygons.

    c. Select the polygon that contains the protective action zone – this is the expansion of the protective action zone to the nearest physical boundaries.

d. Ensure the polygon (new protective action zone) does not contain holes.

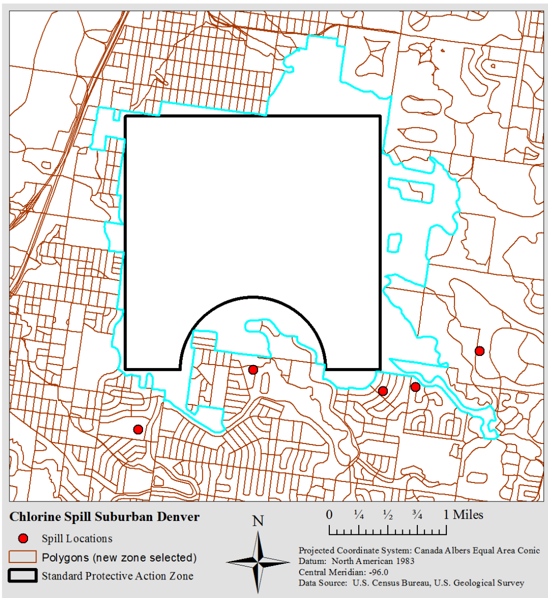

Figure 15: Lines selected for new zone (Step 5c)

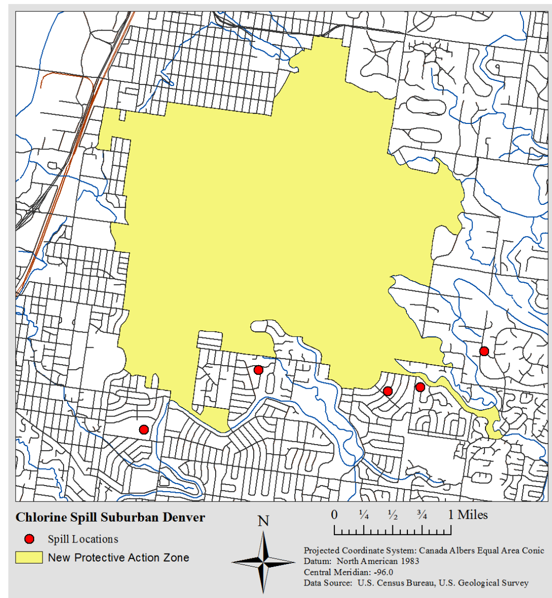

Figure 16: New protective action zone (Step 5c)

e. Subtract from the new protective action zone the area that intersects the new initial isolation zone.

f. Clip census block data by the new protective action zone to determine the population affected.

g. Compile statistics for population and area affected using the same process as step 2d for the protective action zone.

h. Add the total number of intersections in the new initial isolation and protective action zones, and record the sum in the statistics table.

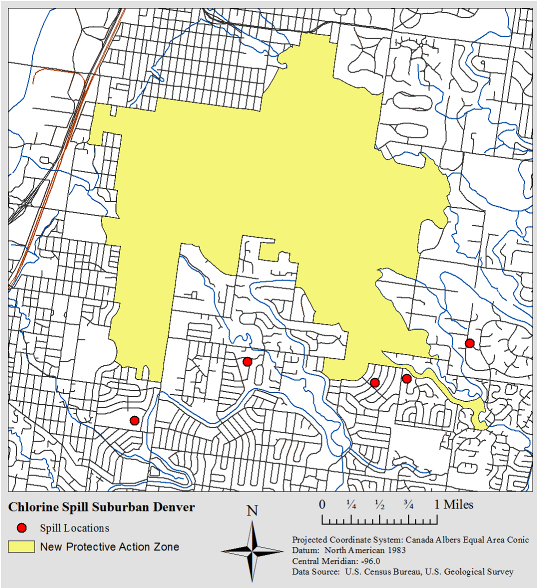

Figure 17: Zone without overlap (Step 5e)

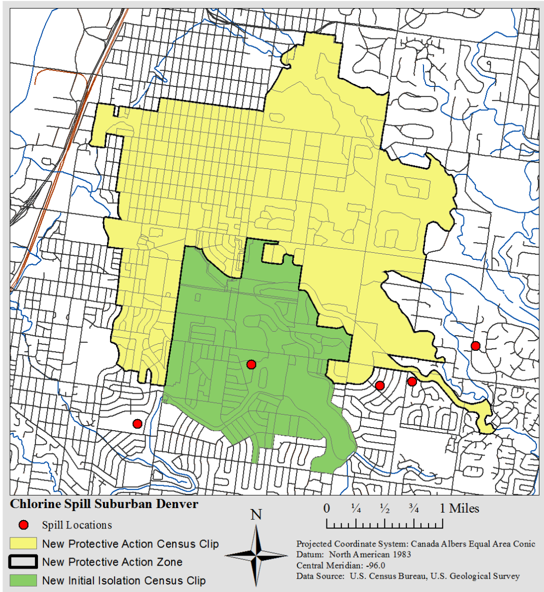

Figure 18: Census data clipped to zone (Step 5f)

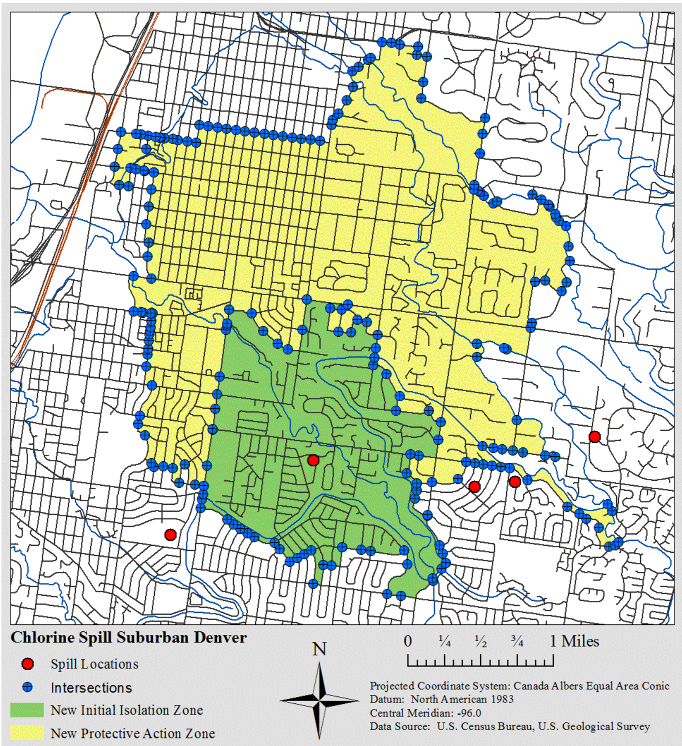

Figure 19: New hazard zone intersections (Step 5h)

At the conclusion of Step 5h, the new initial isolation and protective action zones have been generated, the populations and areas affected by each have been calculated, and the total number of intersections in the new cordons has been counted. This is what the standard hazards zones from Steps 2-3 will be compared to.

i. Calculate statistics to fill in the following columns:

   i. Pop_diff: Subtract the populations affected by the standard hazard zones from the populations affected by the new hazard zones.

   ii. Area_diff: Subtract the areas affected by the standard hazard zones from the areas affected by the new hazard zones.

   iii. Pop_diff_per: Divide the population difference by the standard hazard zones' population to calculate a percent difference.

   iv. Area_diff_per: Divide the area difference by the standard hazard zones' area to calculate a percent difference.

   v. If a new protective action zone does not exist, add a row in table. This can occur if the new initial isolation zone is so large that it encompasses the entire standard protective action zone. In this case, a row is created to calculate and store the same statistics using values of zero for the population and area affected by the new protective action zone.

Table 7: Statistics Table with Standard and New Statistics (Step 5i)

OBJ	FREQ	SUM_Pop_Aff	SUM_Area_Aff	Hazard	Zone	Std_New	Envir	City	Point	Vertices	Boundar	Pop_diff	Area_diff	Pop_diff_per	Area_diff_per
1	86	3239.440021	3141590.064636	1	Initial Isolation	Standard	2	Denver	67	39	NA	-1	-1	<Null>	<Null>
2	326	15102.111448	10679206.13343	1	Protective Action	Standard	2	Denver	67	115	NA	-1	-1	<Null>	<Null>
3	125	5288.296315	5565157.646255	1	Initial Isolation	New	2	Denver	67	75	R	-1	-1	<Null>	<Null>
4	342	18372.880796	20300194.25126	1	Protective Action	New	2	Denver	67	251	R	5320	12044555.	29.001558	87.14806

6. Steps 4 and 5 are repeated for each of four sets of physical boundaries (roads, roads and railroads, roads and rivers, and all three).

Table 8: Statistics Table with All Four Boundary Sets (Step 6)

OBJ	FREQ	SUM_Pop_Aff	SUM_Area_Aff	Hazard	Zone	Std_New	Envir	City	Point	Vertices	Boundar	Pop_diff	Area_diff	Pop_diff_per	Area_diff_per
1	86	3239.440021	3141590.064636	1	Initial Isolation	Standard	2	Denver	67	39	NA	-1	-1	<Null>	<Null>
2	326	15102.111448	10679206.13343	1	Protective Action	Standard	2	Denver	67	115	NA	-1	-1	<Null>	<Null>
3	125	5288.296315	5565157.646255	1	Initial Isolation	New	2	Denver	67	75	R	-1	-1	<Null>	<Null>
4	342	18372.880796	20300194.25126	1	Protective Action	New	2	Denver	67	251	R	5320	12044555.	29.001558	87.14806
5	125	5288.296315	5565157.646255	1	Initial Isolation	New	2	Denver	67	75	RRail	-1	-1	<Null>	<Null>
6	342	18372.880796	20300194.25126	1	Protective Action	New	2	Denver	67	251	RRail	5320	12044555.	29.001558	87.14806
7	122	5284.371986	5560221.371807	1	Initial Isolation	New	2	Denver	67	80	RRiver	-1	-1	<Null>	<Null>
8	301	16549.748316	13316650.54734	1	Protective Action	New	2	Denver	67	240	RRiver	3493	5056075.7	19.040802	36.5831
9	122	5284.371986	5560221.371807	1	Initial Isolation	New	2	Denver	67	80	RRR	-1	-1	<Null>	<Null>
10	301	16549.748316	13316650.54734	1	Protective Action	New	2	Denver	67	240	RRR	3493	5056075.7	19.040802	36.5831

7. Steps 2-6 are repeated for each location point and each hazard type using while and for loops.

As a comparison of different hazards and different environments, Figure 20 shows an overall perspective of the chlorine spill in suburban Denver with both the standard and new hazard zones, and Figure 21 shows an overall perspective of an RDD attack at the same location in suburban Denver. Using a different scale, Figure 22 shows an anhydrous ammonia spill in rural Denver, and Figure 23 shows a VX attack at the same location in rural Denver.

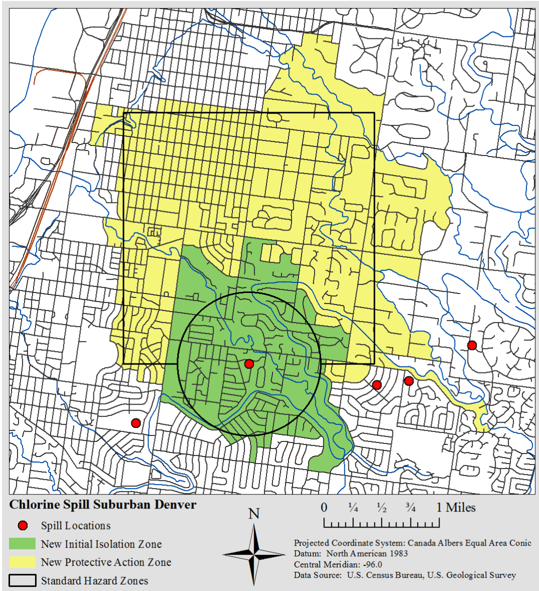

Figure 20: Suburban Denver - Chlorine

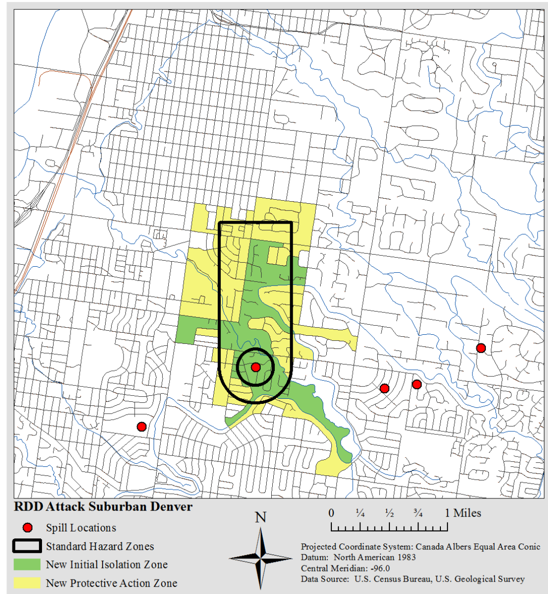

Figure 21: Suburban Denver - RDD

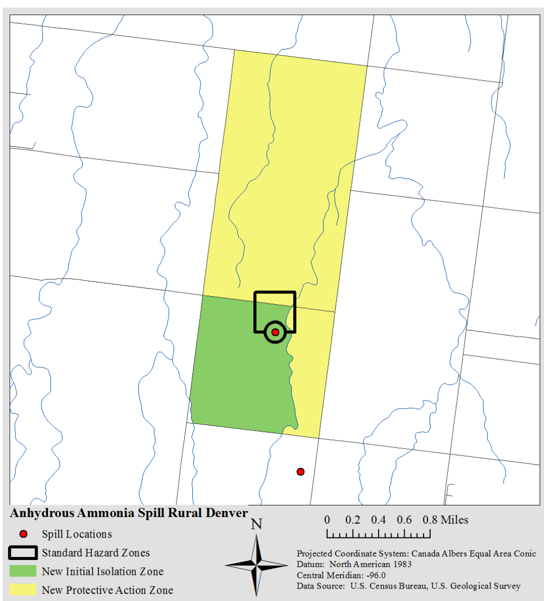

Figure 22: Rural Denver - Anhydrous Ammonia

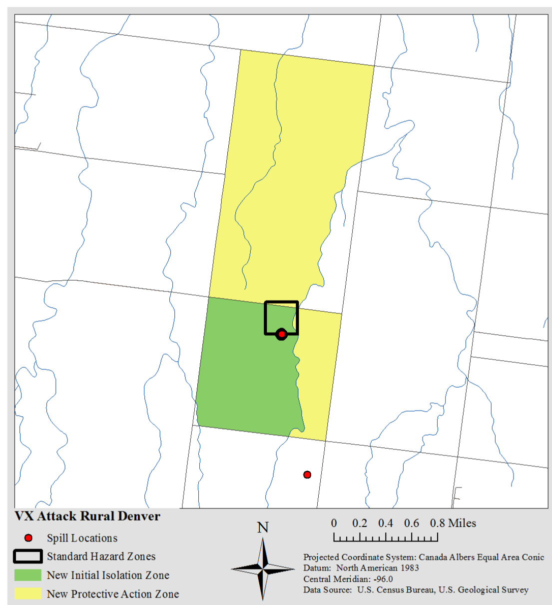

Figure 23: Rural Denver - VX

An ArcGIS® tool was also created following the same general process as outlined above. However, it was designed to be useful as a tool for a specific incident. The basis of this model could be adapted to a tool and integrated with incident management systems for responders to use on-site or in an emergency operations center for a particular incident with a single release. The model prompts the user for the hazard type, wind direction, location name, geodatabase to save outputs to, specific spill location, census data shapefile, and infrastructure shapefile(s). The model outputs the standard and new hazard zone polygons, the areas and populations affected by each zone, and the number of vertices in each polygon. Responders could use this information for decision support during an incident. The script for this tool is in Appendix B.

Statistical Analysis

A statistical analysis was conducted using the ArcGIS® model to answer the research questions. First, a sampling plan was created to determine what and how much data to collect with the model. Then, paired t-tests were conducted to answer the first research question of determining how published hazard zones change when adapted to physical boundaries. An analysis of variance (ANOVA) was conducted to answer the second research question of determining the effects that different environments and locations have on how the hazard zones change when adapted to physical boundaries. To answer the third research question of determining if there exists a set of physical boundaries that improves responder efficiency, a comparison of mean number of intersections was performed to select the boundary set with the fewest intersections.

Sampling Plan

A sampling plan was created to generate the data needed to answer the research questions. To determine a sufficient number of specific release locations for each scenario (city, area, and hazard), a power analysis was conducted to detect a practical difference in areas and populations between the standard and new hazard zones. Each release location was associated with six theoretical releases to account for each hazard type. Each theoretical release generated nine statistics of interest:

- Difference in populations affected by standard and new hazard zones
- Difference in areas affected by standard and new hazard zones
- Percent change in population affected by new hazard zone
- Percent change in area affected by new hazard zone
- Intersections in standard hazard zones
- Intersections in new hazard zones using roads
- Intersections in new hazard zones using roads and railroads
- Intersections in new hazard zones using roads and rivers
- Intersections in new hazard zones using roads, railroads, and rivers

A proxy variable was used to represent responder efficiency. The number of intersections in the final polygons generated for the new zones matched to physical boundaries was used (note that "intersection" represents a physical connection such as a road intersection rather than the set theory function as used in ArcGIS®). The intersections occur between any two boundaries (i.e., road, railroad, or river) included in the new hazard zone or with a boundary that crosses the hazard zone. Therefore, more complex shapes involving more intersections and turns were considered to have lower responder efficiency. To determine a sufficient sample size for detecting the boundary set with fewest intersections, a select the best procedure was used. The initial phase simply used the data already generated for the first and second research questions;

additional data was generated as needed for the secondary phase. Additionally, the intersections in the new hazard zones were compared with the intersections in the standard hazard zone. For the standard hazard zones, only physical boundaries that crossed the hazard zone cordon were counted, because the hazard zones do not follow physical boundary lines. Roads, railroads, and rivers crossing the cordon of the standard hazard zones were included.

Practical Differences

Responders, local officials, and the local population are all affected by the size, shape, and location of hazard zones. A larger area to establish a cordon around could require more responders and more time to set up and maintain. This is especially true in an urban environment, but may be less true in a rural environment. From the perspective of the population affected, a larger area might impact travel in the surrounding region and might take longer to complete an evacuation. A larger population means that protective actions have to be implemented by more people. This could result in longer implementation times and more complex communication needs. For evacuations, a larger population can result in a greater traffic and pedestrian burden. A greater evacuation distance from a larger area and/or a larger evacuating population also increases risk of travel-related accidents. Finally, the number of people affected by a hazard zone could influence the responders' decision to initiate an evacuation or shelter-in-place order and the timing of those decisions.

What constitutes a practical difference between populations and areas depends on many variables. The degree to which a larger area or population will influence outcomes such as response time, evacuation-related accidents, and communication networks depends on the specific scenario. For example, the road network in a given location may be robust against large increases in evacuation traffic, but the road network in a different location may get congested with even a small increase in traffic. Another variable influencing the impact of an increase in area or population is the community's response capability. A larger response force or more advanced technology may make emergency responders more resilient to larger or more complex hazard zones.

Because of the many variables involved in defining a practical difference from one scenario to the next, this research considered a more objective measure to compare differences against. This allows the reader to use the results to determine how important the difference is to their situation with an established reference point. The measure selected was average census block size and population for the areas of interest. Census tracts generally range from 1,200 to 8,000 people with an optimal population of 4,000 people. Block-groups generally range from 600 to 3,000 people (U.S. Census Bureau, 2010). Census blocks are bounded by physical features and vary considerably in size and population across the U.S., especially in less populated or rural areas. Distributions of population and size by census block are strongly skewed positive. Because of this variation and distribution, census block averages may not be meaningful when considering an individual scenario. They are only used as practical differences, because they are an objective and consistent value.

The national average census block size is 0.344 square miles (0.361 square miles when water-only blocks are excluded). The national average census block population is 27.9 people (29.3 people when water-only blocks are excluded). Averages for the three states of interest are given in Table 9. Considering smaller areas of interest within the state (e.g. Chicago and surrounding area) and excluding obvious outliers (e.g. Lake Michigan), the averages do not change significantly from the state-wide averages. Many census blocks have a population of zero, so averages were also considered using only blocks with a nonzero population. Based on these values, practical differences were defined as 0.35 square miles and 50 people.

Table 9: Average Block Sizes and Populations

State	Average Block Area (sq mi)	Average Block Area (no water-only blocks)	Average Block Population	Average Block Population (where people live)
Colorado	0.518	0.534	25.1	42.7
Illinois	0.128	0.132	28.4	47.9
Texas	0.294	0.307	27.6	55.3

Because the number of intersections is a proxy variable rather than a direct measure, a practically significant value is difficult to meaningfully define. After a small sample of 270 data points was generated, the practical difference was defined as approximately 10% of the mean. This resulted in a practical difference of 15 intersections.

Power Analysis

A power analysis was performed in JMP®. To estimate the variance, a small sample of 270 total data points was generated. The practical difference was used as described in the previous section, a significance level of 0.05 was chosen, and a power of 0.80 was chosen. Equation 1 was solved for sample size n by JMP® to find the required sample size, where F is the F-distribution, f is the f statistic, ϵ is the practical significance value or difference to detect, and σ is the estimated standard deviation (Barker, 2011).

Equation 1 (Barker, 2011)

$$Power = Probability\left[f > f_{crit} \mid f \sim F\left(1, n-1, \frac{n\epsilon^2}{\sigma^2}\right)\right]$$

Based on this analysis, the required sample sizes are very large, ranging from about 8,000 to a few million points. Fortunately, the initial sample also showed very large means for population and area differences (about 3.8 square miles and 2,500 people), so the actual differences appear to be much larger than the selected practical differences. Considering practical limitations of time, as much data as reasonable was generated, and the results were monitored to verify that sufficient power would be attained.

Statistical Comparison: Research Question 1

How do published emergency hazard zones for various CBRNE incidents change when adapted to physical boundaries?

A statistical analysis was used to compare the areas and populations of the standard hazard zones and the expanded hazard zones. To answer the first research question, all the standard zones and expanded zones were compared in one-sided paired t-tests. The paired t-tests considered the difference in total area affected, the difference in total population affected, the percent difference in area affected, and the percent difference in population affected. To mitigate possible issues with independence, the data was sorted by hazard into six subsets. This resulted in 24 totals t-tests and confidence intervals.

A significance level of 0.05 was initially selected. Initially, a conservative approach to controlling error rates due to multiple tests was balanced with retaining sufficient power to detect significant differences. However, because the actual differences were much larger than the practical differences, a less conservative approach was deemed unnecessary. Therefore, Bonferroni's approach was used to split the error rate among all 24 tests. The significance level for each individual test was 0.002. The differences are calculated as shown in Equation 2. Because the algorithm restricts the hazard zones from shrinking, the expected result is a significant difference in which the new zones are larger. Thus, a one-sided t-test is appropriate.

Equation 2

$$\mu_d = \mu_{new} - \mu_{standard}$$

$$\bar{d} = \bar{d}_{new} - \bar{d}_{standard}$$

The paired difference is defined as the new zone value minus the standard zone value, so that the expected difference is positive. Equation 3 shows the test hypotheses and the test statistic t. The null hypothesis is that the mean paired difference or percent difference is less than or equal to zero; in other words, the null hypothesis states that the new hazard zones affect no more area or population than the standard hazard zones. The alternate hypothesis is that the paired or percent difference is greater than zero, such that the new hazard zones affect a greater area or population than the standard hazard zones.

Equation 3

$$H_0\colon\ \mu_d \leq 0$$

$$H_a\colon\ \mu_d > 0$$

$$t = \frac{\bar{d}}{s_d / \sqrt{n_d}}$$

The rejection region is defined as $t > t_\alpha$ based on (n_d – 1) degrees of freedom, where n_d is the sample size.

To better describe the difference and practical significance of the results, confidence intervals were constructed for each of the paired difference tests. Equation 4 is used to construct the confidence intervals.

Equation 4

$$\bar{d} \pm t_{\alpha/2} \frac{s_d}{\sqrt{n_d}}$$

where $\bar{d}$ is the mean paired difference, $t_{\alpha/2}$ is the t-statistic associated with the significance level α, s_d is the sample standard deviation, and n_d is the sample size. The significance level is 0.002.

The t-test relies on the assumptions of normality and independent sampling. With a sufficiently large sample size, the Central Limit Theorem ensures an approximately normal distribution of the sample mean. A large sample size is typically defined as at least 30 data points; this study exceeds that sample size. To ensure independent sampling, the release locations were selected randomly within each region.

Statistical Comparison: Research Question 2

What effects do different environments and locations have on emergency hazard zones when the zones are adapted to physical boundaries?

To answer the second research question, two ANOVAs were conducted with response variables of paired differences of population affected and area affected and factors of hazard, city, and environment. Additionally, all interactions were included for a total of seven factors. The response is expected to vary based on hazard, because the prescribed distances vary. Therefore, hazard was included in the analysis to reduce the error in the other factors. City had three levels of Chicago, Houston, and Denver, and environment had three levels of urban, suburban, and rural. Figure 24 illustrates the ANOVAs.

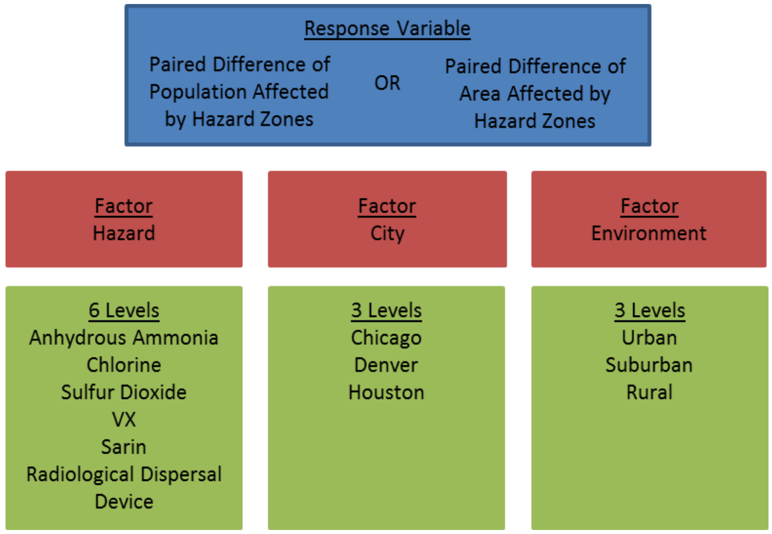

Figure 24: ANOVAs

The null hypothesis is that none of the factors explain the response; the alternate hypothesis is that at least one of the factors explains the response. If the ANOVA F-test indicates that at least one of the factors influences the response at a significance level of 0.05, then effect tests and least squares means plots will be considered. Additionally, a Tukey test was conducted to analyze pair-wise comparisons with an experiment-wise significance level of 0.05.

The internal validity of the ANOVA F-Test relies on three assumptions: normality, constant variance, and independence. To test normality, the residuals were plotted, and a goodness of fit test was conducted. The null hypothesis is that the distribution of residuals is normal. To test for constant variance, a Breusch-Pagan test was conducted. The null hypothesis is that variance is constant across groups. A significance level of 0.05 was used for each test.

Statistical Comparison: Research Question 3

Is there a preferred set of physical boundaries that improves responder efficiency?

To answer the third research question, the boundary set with the fewest intersections was determined through a selection of the best method using a minimization goal. The initial phase screens out any of the four boundary sets that have intersection counts sufficiently large to be rejected as not the best set at an overall confidence level of 95%. The boundary set with the smallest mean number of intersections is compared to each of the other three boundary sets. A given boundary set *i* is retained if the mean number of intersections for that boundary set, $\bar{v}_i$, is sufficiently close to the smallest sample mean number of intersections, $\bar{v}_j$. Equation 5 defines this sufficiently close difference. W_{ij} is the margin of error for the two boundary sets *i* and *j* using a t-statistic with $[1-\left(1-\frac{\alpha}{2}\right)^{\frac{1}{3}}, R_0-1]$ degrees of freedom, where R_0 is the sample size. The practical difference is designated ϵ.

Equation 5

$$\bar{v}_i - \bar{v}_j \leq \max\{0, W_{ij} - \epsilon\}$$

The number of replications to generate for the initial phase was determined by the sampling plan based on practical and statistical differences for Research Question 1. Additional data for the retained boundary sets will be generated as required in the secondary phase to select-the-best or near-best boundary set at a confidence level of 95%. A near-best boundary set would be a boundary set that may or may not be the absolute best solution, but is at least within the range deemed to be practically significant. Additionally, the method was repeated including the standard hazard zone intersections, which resulted in a total of five systems to compare. The method outlined by Banks, Carson, Nelson, and Nicol (2010) was used to perform the statistical calculations and determine the final sample size.

Additionally, an ANOVA was conducted using the response variable of number of intersections, a main effect of boundary set, and a blocking effect of scenario. Scenario is defined as a random point location and hazard type combination. The blocked ANOVA allows for greater power and insight into the question, because each scenario is associated with four observations in the dataset – one for each boundary set in the new hazard zones. Including scenario in the ANOVA reduces the variance due to hazard and point location, such that effects from boundary set are clearer.

The select-the-best procedure uses the t-statistic, and the same assumptions must be satisfied. The sample size is sufficient to rely on the Central Limit Theorem to ensure normality, and the release locations were selected randomly within each region to satisfy the condition of independence. The ANOVA must satisfy the assumptions noted for Research Question 2; that is, normality of residuals, constant variance, and independence.

Summary

The methodology employed in this research study included three main stages. First, the hazard release locations were selected through an analysis of historical data. Second, a model was developed using ArcGIS® and python scripting to automate the process of generating standard and new hazard zones and collecting the relevant data. Third, prospective statistical analyses were described to answer the research questions.

IV. Analysis and Results

Chapter Overview

This chapter will discuss the results of the hazard zones simulation. Almost 1,000 points (release locations) were generated, resulting in almost 6,000 scenarios (location and hazard). This produced 53,460 relevant statistics to conduct the analysis. This chapter will answer each of the three research questions using the methodology outlined in the statistical analysis section of Chapter III. The results show that standard initial isolation and protective action zones do change when adapted to physical boundaries. In general, both population and area change significantly from both a statistical and practical perspective. Environment (urban, suburban, rural) has a strong effect on how much hazard zones change, and location (Chicago, Denver, Houston) has a lesser but still noticeable effect. Finally, the boundary set used to create the new hazard zones has a statistically significant, but practically insignificant, effect on the number of intersections in the hazard zone cordons.

Research Question 1

How do published emergency hazard zones for various CBRNE incidents change when adapted to physical boundaries?

To answer Research Question 1, t-tests were conducted and confidence intervals were constructed for the population difference, area difference, percent population difference, and percent area difference. To mitigate concerns about independence, the data was split by hazard. This resulted in 24 one-sided t-tests and 24 confidence intervals. A significance level of 0.05/24 = 0.002 for each test and confidence interval was used. While this is probably overly conservative, the results were still significant with high power. Summary statistics of the results are shown in Tables 10-16. Confidence intervals were calculated for the median rather than the mean, because the distributions were strongly skewed right. Minimums and maximums show the range of extremes. The p-values shown in the tables are for the Wilcoxon signed-rank test. Paired t-tests were also conducted with similar results; all 24 t-tests were statistically significant at 0.002. Additionally, Figure 25 and Figure 26 show boxplots for the four response variables by hazard to better illustrate the overall results. Forty six particularly large outliers were removed from Figure 26 to more clearly show the boxplots.

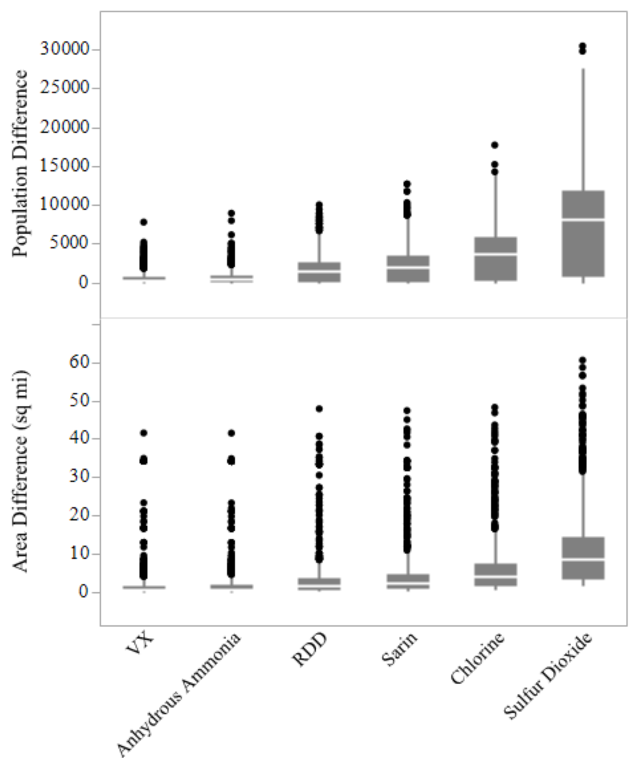

Figure 25: Boxplots for Population and Area Difference

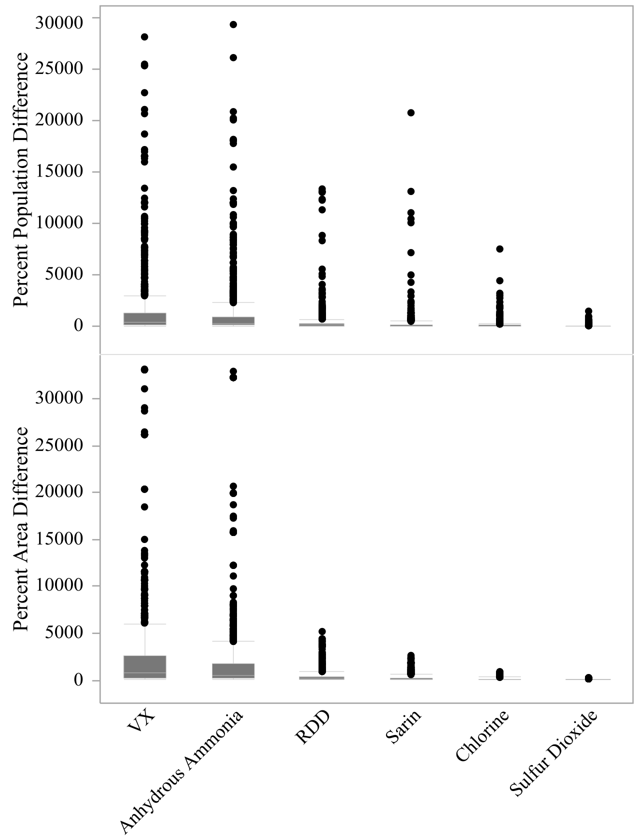

Figure 26: Boxplots for Population and Area Percent Difference

Table 10: Summary Statistics (Anhydrous Ammonia)

	Population Difference	Area Difference (square miles)	Percent Population Difference	Percent Area Difference
Median	449	0.63	330	596
99.8% CI	350 – 542	0.50 – 0.83	274 – 417	474 – 779
Minimum	0	0.048	0	45.4
Maximum	8946	41.53	271,557	39,178
Mean	685	2.09	2,087	1,972
Standard Deviation	893	4.75	10,685	4,479
P-value	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Power	1	1	0.99999	1

Table 11: Summary Statistics (Chlorine)

	Population Difference	Area Difference (square miles)	Percent Population Difference	Percent Area Difference
Median	3,648	4.24	43.6	79.49
99.8% CI	3,219 – 4,045	3.43 – 5.01	35.7 – 51.1	64.35 – 93.94
Minimum	1	0.54	0	10.09
Maximum	17,730	48.26	7,544	904.3
Mean	3,869	6.26	130	117.2
Standard Deviation	3,464	7.22	384	135.3
P-value	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Power	1	1	1	1

Table 12: Summary Statistics (Sulfur Dioxide)

	Population Difference	Area Difference (square miles)	Percent Population Difference	Percent Area Difference
Median	8,073	8.81	18.6	38.45
99.8% CI	7,343 – 8,755	7.64 – 10.23	16.5 – 21.0	33.4 – 44.7
Minimum	3	1.58	0	6.91
Maximum	30,499	60.56	1,502	264
Mean	7,743	11.44	45.3	49.9
Standard Deviation	6381	10.14	93.8	44.3
P-value	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Power	1	1	1	1

Table 13: Summary Statistics (VX)

	Population Difference	Area Difference (square miles)	Percent Population Difference	Percent Area Difference
Median	342	0.57	445	883.5
99.8% CI	277 – 417	0.44 – 0.71	372 – 540	686 – 1,114
Minimum	0	0.031	0	47.76
Maximum	7,800	41.57	271,557	64,996
Mean	572	1.97	2,705	3,074
Standard Deviation	769	4.72	13,250	7,374
P-value	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Power	1	1	1	1

Table 14: Summary Statistics (Sarin)

	Population Difference	Area Difference (square miles)	Percent Population Difference	Percent Area Difference
Median	2,071	2.44	75.6	135.4
99.8% CI	1,689 – 2,369	2.14 – 2.80	65.5 – 95.0	118.6 – 155.8
Minimum	0	0.26	0	14.4
Maximum	12,722	47.40	114,932	2,634
Mean	2,328	4.32	436	240
Standard Deviation	2,237	6.29	4,097	349.3
P-value	< 0.0001	< 0.0001	< 0.0001	< 0.0001
Power	1	1	0.91707	1

Table 15: Summary Statistics (RDD)

	Population Difference	Area Difference (square miles)	Percent Population Difference	Percent Area Difference
Median	1,517	1.88	122	203.6
99.8% CI	1,243 – 1,744	1.56 – 2.15	102 – 155	169 – 233
Minimum	0	0.17	0	18.7
Maximum	10,028	47.87	172,564	5,182
Mean	1,830	3.60	578	390
Standard Deviation	1,840	5.96	5,607	644.9
P-value	< 0.0001	< 0.0001	0.0006	< 0.0001
Power	1	1	0.89956	1

The median population differences range from 342 people (VX) to 8,073 people (sulfur dioxide). Taking into account the confidence intervals, we would expect even the smallest median population difference to be at least 277 people. This is significant both statistically and compared to the nominal practical difference of 50 people. However, due to the skewed nature of the distributions, 927 observations (almost 17% of all observations) had population differences of less than 50 people. The smallest observed population difference was 0, which occurred 57 times (1%); these observations were mostly associated with small standard hazard zones or rural areas, and all occurred where the standard hazard zones affected zero population. The largest observed population difference was 30,499. This occurred in suburban Houston with sulfur dioxide, which has the largest standard hazard zone area. There were 38 observations (0.7%) with population differences over 20,000 and 135 observations (2.5%) over 15,000.

The median area differences range from 0.57 (VX) to 8.81 (sulfur dioxide) square miles. Taking into account the confidence intervals, we would expect even the smallest median area difference to be at least 0.44 square miles. This is significant both statistically and compared to the nominal practical difference of 0.35 square miles. The smallest expansion observed was 0.031 square miles (VX in urban Houston), and the maximum was approximately 60 square miles (sulfur dioxide in rural Denver). Similar to the distribution of population differences, the distribution of area differences displays a skewed shape. There are 887 observations (15% of all observations) with an area difference less than the practical difference of 0.35 square miles and 1,201 (20%) with an area difference less than 0.5 square miles. There are 47 observations (0.8%) with an area difference greater than 40 square miles and 305 (5%) with a difference greater than 20 square miles.

Percent differences help describe changes relative to the standard hazard zones. Median percent differences in population range from 18.6% (sulfur dioxide) to 445% (VX). Some standard hazard zones did not affect any population; to avoid dividing by zero when calculating percent differences, all standard population values were increased by one. Still, many standard zones affected a very small number of people, which resulted in some very large percent changes. The maximum percent difference in population was 271,557%. This occurred for both VX and anhydrous ammonia in suburban Denver; the population increased from 0 (which was corrected to 1) to 2,716. For 771 observations (13% of all observations), the percent change was less than 15%. For 2,986 observations, or about half of all points, the population affected by the new hazard zones more than doubled compared to the standard hazard zones.

The median percent differences in area range from 38.5% (sulfur dioxide) to 884% (VX). The largest percent area difference observed was almost 65,000% (VX in rural Denver), and the smallest was 6.9% (sulfur dioxide in urban Chicago). There were 290 observations (5% of all observations) with a change of less than 15% and 1,380 (23%) with a change of less than 50%. For 3,573 observations (60%), the area affected by the new hazard zones was at least twice the area affected by the standard hazard zone.

Correlations

Standard total hazard zone areas are listed in Table 16 to compare the area of the six hazards' standard zones. In general, the hazards starting with larger standard zones are associated with larger population and area differences between the standard and new zones. The hazards with larger standard zones also appear to have smaller percent differences between the standard and new zones. This is supported by examining correlations between the response summary statistics and the standard hazard zone areas.

Table 16: Standard Hazard Areas

Hazard	Total Hazard Zone Area (square miles)
Anhydrous Ammonia	0.106
Chlorine	5.336
Sulfur Dioxide	22.91
VX	0.064
Sarin	1.800
RDD	0.924

The first analysis ($n=6$) calculated the correlations between each hazard's mean or median value and the total hazard zone area. The medians were plotted against standard zone areas with linear regression lines fitted to each plot in Figure 27, where the shaded area shows the 95% confidence interval about the fit line. For the population and area difference variables, there are strong positive correlations between the medians and means and the standard hazard zone areas, which means that larger original protective distances result in more people and area affected. For the percent population and percent area differences, there are moderate negative correlations between the medians and means and the standard hazard zone areas, which means that larger original protective distances generally result in smaller percent increases in people and area affected.

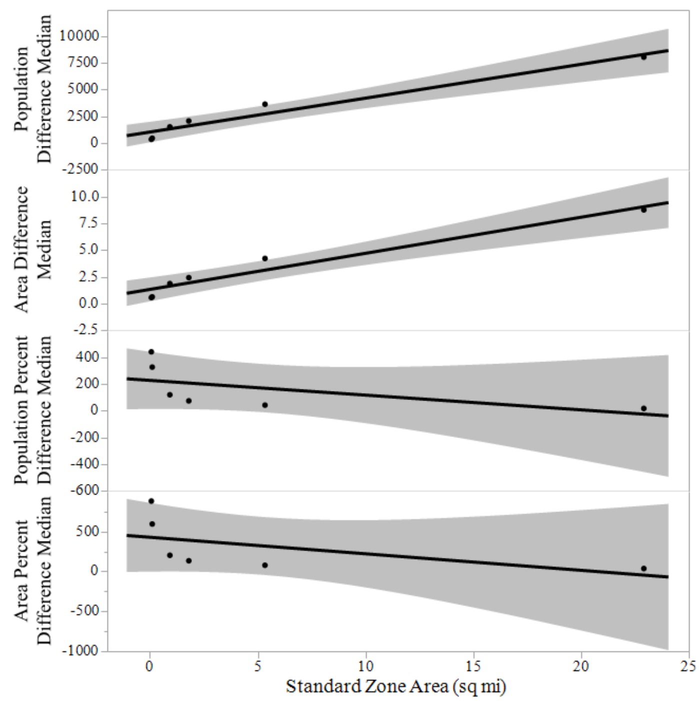

Figure 27: Population and Area Differences vs. Standard Zone Areas

Table 17: Standard Area Correlations with Summary Statistics

	Standard Hazard Zone Area		
	Linear	**Square Root**	**Logarithmic**
Population Difference – *Median*	0.9755	0.9996	
Population Difference – *Mean*	0.9666	0.9998	
Area Difference – *Median*	0.9710	0.9999	
Area Difference – *Mean*	0.9674	0.9998	
Percent Population Difference – *Median*	-0.5683		-0.9427
Percent Population Difference – *Mean*	-0.5548		-0.9393
Percent Area Difference – *Median*	-0.5417		-0.9246
Percent Area Difference – *Mean*	-0.4900		-0.8974

To further investigate these relationships, correlations between each of the response variables and the standard hazard zone areas were calculated using the entire dataset (*n=5,940*). The data were plotted against standard zone areas with linear regression lines fitted to each plot in Figure 28. Additionally, the same transformations were conducted on the complete dataset: square root for population and area difference and logarithmic for percent differences. These transformations increased the correlation magnitudes. The linear, square root, and logarithmic correlations are shown in Table 18. For the population and area difference, moderate positive correlations exist with the standard hazard area, which means that larger original protective distances result in more people and area affected, but the association is weaker than the first analysis that used only the summary statistics. For the percent differences, weak (but still statistically significant) negative correlations exist with the standard hazard area, which means that larger original protective distances tend to result in smaller percent increases in people and area affected, but the association is not nearly as strong and may not be useful. The summary statistics and both sets of correlations suggest that there is a significant relationship between the response variables and the standard hazard areas, but there is also considerable variation in the data.

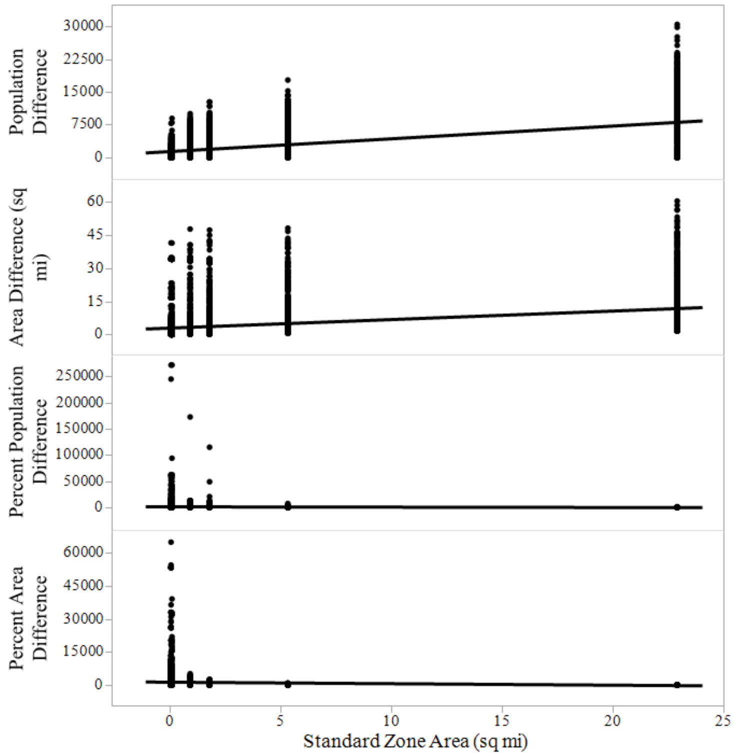

Figure 28: Population and Area Percent Differences vs. Standard Zone Areas

Table 18: Standard Area Correlations with Complete Sample Data

	Standard Hazard Zone Area		
	Linear	**Square Root**	**Logarithmic**
Population Difference – *All Data*	0.5854	0.6056	
Area Difference – *All Data*	0.4183	0.4323	
Percent Population Difference – *All Data*	-0.0748		-0.1266
Percent Area Difference – *All Data*	-0.1511		-0.2768

Discussion

Paired differences for population and area, as well as percent changes, were found to be statistically and practically significant for each hazard. This analysis found a general relationship between standard hazard zone size and the population and area differences affected by the new hazard zones. Larger standard hazard zones tended to grow more in terms of the absolute population and area affected, but the percent changes tended to be smaller. For example, sulfur dioxide has the largest standard hazard area at almost 23 square miles, had a median population increase of over 8,000 people and 18.6%, and experienced a median area growth of 8.8 square miles and 38.5%. Comparatively, VX has the smallest standard hazard area at 0.064 square miles, saw a median population increase of 342 people and 445%, and a median area growth of 0.6 square miles and 884%. This relationship makes sense, because each zone expands in all directions until a new cordon can be constructed using physical boundaries, resulting in a larger total area affected by the new zone when the initial zone is large. Larger areas are likely to affect more people, especially in populated areas. The percent change represents the increase relative to standard size and shows the opposite relationship, likely because the standard zone values serve as the denominators. There was, however, significant variation in the data, such that these relationships did not hold at every data point, and not every point had a practically significant change from the standard hazard zones. This research shows that expanding zones to nearby physical boundaries makes a significant difference in how many people and how much area are likely to impacted by protective action orders, such as evacuation or shelter-in-place, but the specific impact depends on the hazard and location.

Research Question 2

What effects do different environments and locations have on emergency hazard zones when the zones are adapted to physical boundaries?

To answer Research Question 2, two ANOVAs were conducted with response variables of population difference and area difference. A full-factorial design with hazard, city, and environment resulted in seven factors in each model; after examining the initial model, some interactions were removed. Assumptions of constant variance, normality, and independence were considered.

Assumptions

The residual by predicted plot for both ANOVAs showed highly non-constant variance. To deal with this deviation, a square root transformation was applied to the response variables. The breusch-pagan tests resulted in very small p-values. However, the plots with the transformed variables show significantly less variation in the variances and little to no pattern (see Figure 29). Because the ANOVA is fairly robust against deviations of non-constant variance, and the sample sizes are equal, this deviation is unlikely to cause any issues related to statistical validity.

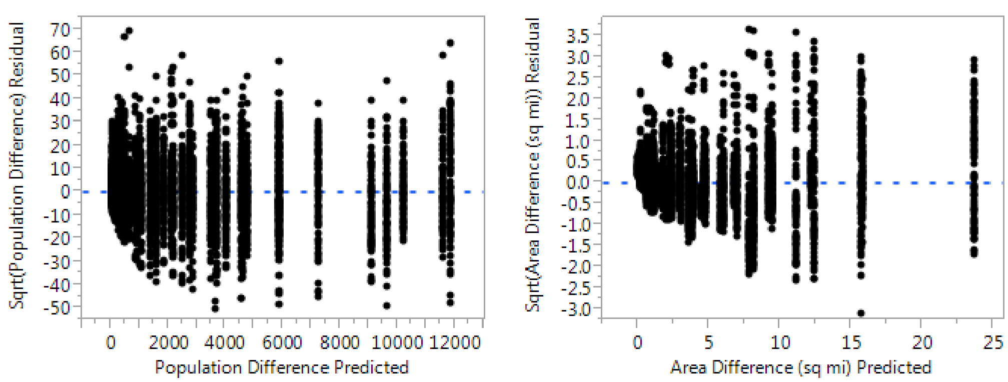

Figure 29: Residuals vs Predicted (Square Root Transformations)

The distribution of residuals shows a generally normal shape for both ANOVAs. The distributions are shown in Figure 30 and Figure 31. While the KSL goodness of fit tests resulted in p-values of 0.01, which is less than the significance level of 0.05, this is likely due to the large sample size. The distribution has a single, central peak and mostly normal appearance, and the ANOVA is robust against deviations of non-normality, so this assumption is sufficiently met.

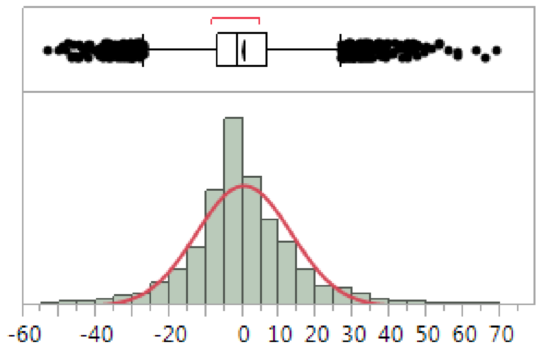

Figure 30: Population Difference ANOVA Residuals

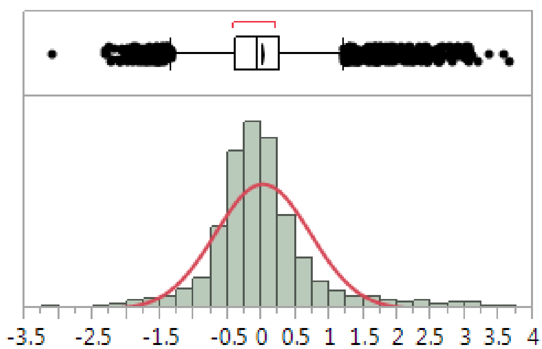

Figure 31: Area Difference ANOVA Residuals

Independence was established through the design of the simulation and ANOVA. The simulation randomly generated spill locations. Six hazard zones were generated for each spill location – one for each hazard. To mitigate concerns about independence and to provide more insight into the effects of interest, hazard was included as an effect.

Population Difference ANOVA

Once assumptions were adequately met, the effects in the models were considered. Because the sample size is large, effects have a tendency to produce statistically significant results with very small p-values. Therefore, each interaction effect was examined visually to determine if a meaningful interaction was present. For the population difference ANOVA, two interactions were removed. The three-way interaction, while statistically significant, showed little variation in the least squares (LS) means plot. Additionally, City x Hazard had a comparatively low F Ratio (6.4) and displayed little interaction in the LS means plot, which is shown in Figure 32. The R-squared value decreased only a small amount (0.8606 to 0.8543) when removing these interactions.

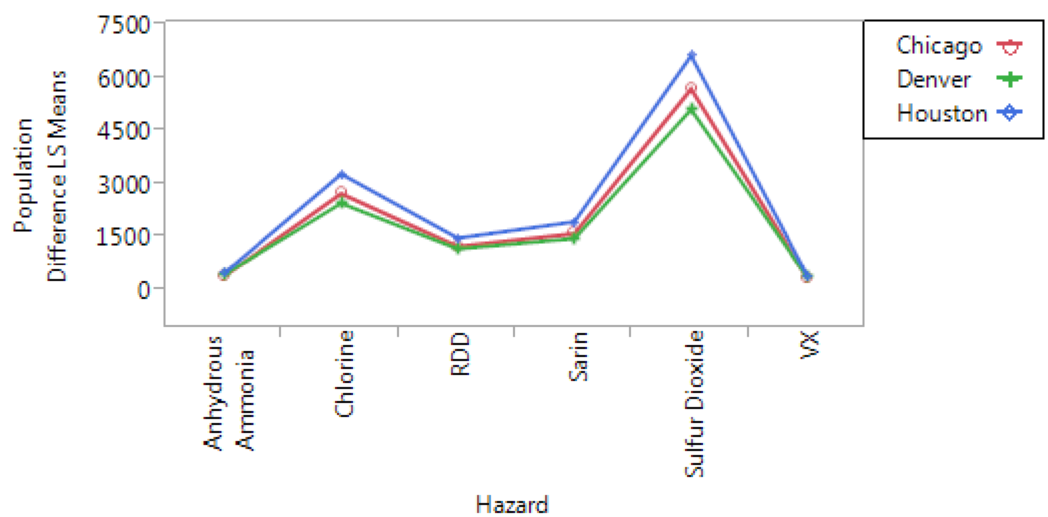

Figure 32: LS Means Plot of City x Hazard for Population Difference ANOVA

Removing two interactions left five factors consisting of three main effects and two interactions in the final model. A summary of the effects included is shown in Table 19. Environment appears to have a particularly pronounced effect on the response variable of population difference. The LS means plot is shown in Figure 33, in which the error bars represent the 95% confidence interval about the mean. Rural areas are associated with significantly less growth in the population affected by the new hazard zones compared to the standard hazard zones. Suburban regions are associated with the greatest growth in population affected. A Tukey test reveals that all three levels are significantly different.

Table 19: Effect Tests for Population Difference ANOVA

Source	Degrees of Freedom	Sum of Squares	F Ratio	P-value
Hazard	5	2,256,778	2,677	< 0.0001
Environment	2	2,757,347	8,177	< 0.0001
City	2	26,710	79	< 0.0001
City x Environment	4	141,006	209	< 0.0001
Environment x Hazard	10	665,967	395	< 0.0001

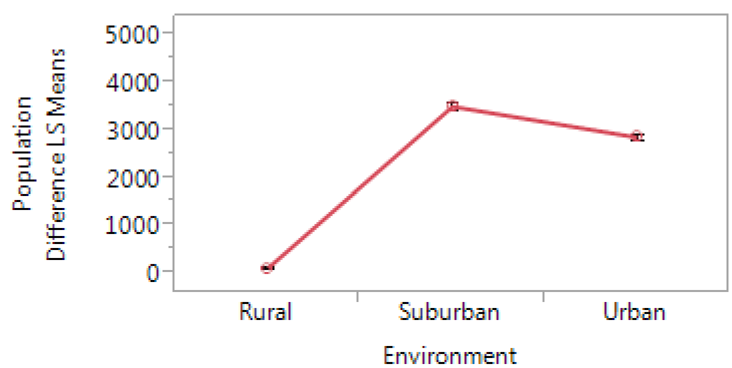

Figure 33: LS Means Plot of Environment for Population Difference ANOVA

As expected, hazard also has a clear effect on the response variable of population difference. The LS means plot is shown in Figure 34. Sulfur dioxide, which has the largest standard hazard zone, shows the greatest difference in the populations affected by new and standard zones. VX has the smallest standard hazard zone and shows the least difference between populations affected by new and standard zones. According to the Tukey test, all six hazards are statistically different.

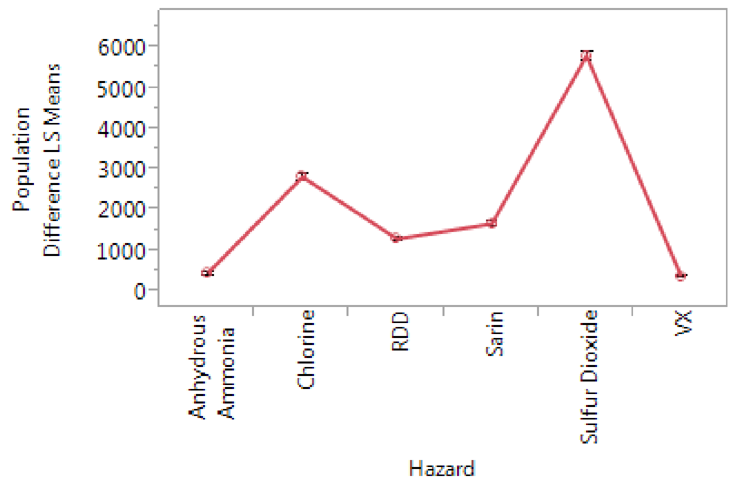

Figure 34: LS Means Plot of Hazard for Population Difference ANOVA

The city has a less pronounced, but still significant, effect on the response. The LS means plot is shown in Figure 35. The difference between Chicago and Denver is statistically significant, but appears to be small. Houston shows a larger growth in population than Chicago and Denver. There are many possible explanations for this difference. For example, city planning strategies might result in different road networks or geographic distributions of residents.

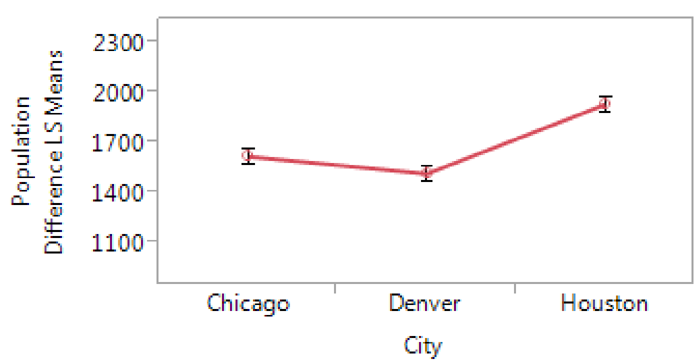

Figure 35: LS Means Plot of City for Population Difference ANOVA

Two interactions of interest were included in the ANOVA. The LS means plots for City x Environment and Environment x Hazard are shown in Figure 36 and Figure 37. While the differences between the rural regions for all three cities are statistically insignificant, the differences between the cities in suburban and urban regions are significant. In both cases, Houston shows more population growth than Denver. However, Chicago shows the least population growth in suburban regions, but the most population growth in urban regions. Rural regions also show little to no significant difference across the six hazards; all six hazards result in small population increases as the hazard zones are expanded to nearby physical boundaries in rural regions. There is much more variation across hazards in urban and suburban regions. Both urban and suburban regions follow a pattern similar to that shown in the main effect of hazard with suburban regions having slightly larger population differences than urban regions.

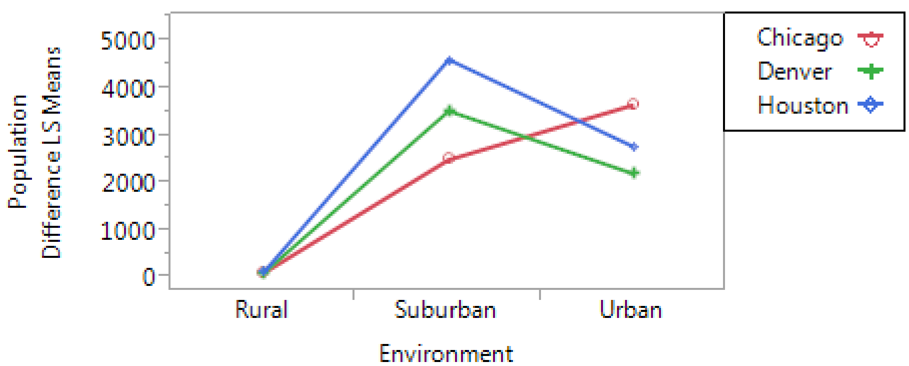

Figure 36: LS Means Plot of City x Environment for Population Difference ANOVA

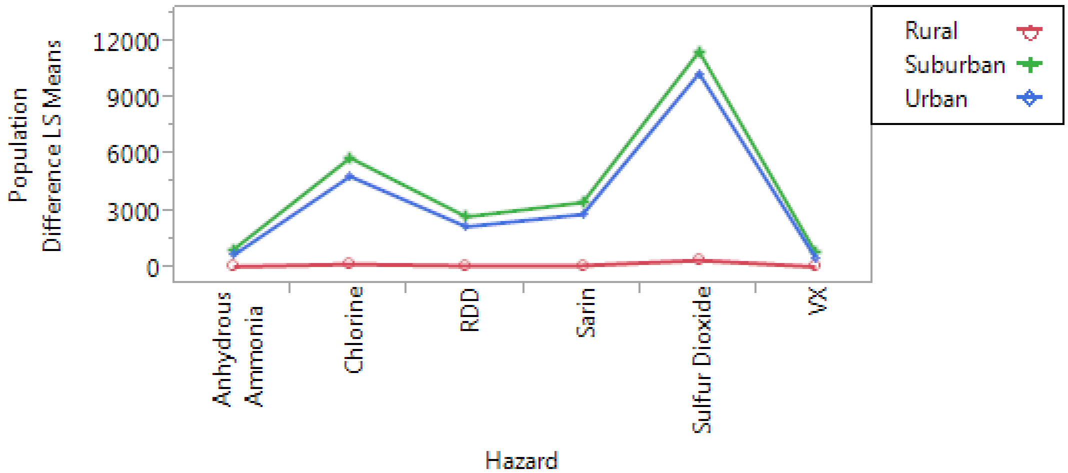

Figure 37: LS Means Plot of Environment x Hazard for Population Difference ANOVA

Area Difference ANOVA

For the area difference ANOVA, one interaction, City x Hazard, was not significant, so it was removed. While statistically significant, two other interactions, Environment x Hazard and the three way interaction City x Environment x Hazard, had comparatively small F Ratios. The LS means plots showed some interactions, but not strong interactions. As a result of this investigation, those three interactions were removed from the model. The R-squared value decreased a small amount (0.7354 to 0.7136) after these interactions were removed. The remaining effects in the final model are shown in Table 20.

Table 20: Effect Tests for Area Difference ANOVA

Source	Degrees of Freedom	Sum of Squares	F Ratio	P-value
Hazard	5	2,980.2	1,211.6	< 0.0001
Environment	2	3,588.1	3,646.7	< 0.0001
City	2	99.4	101.1	< 0.0001
City x Environment	4	594.9	302.3	< 0.0001

In particular, the environment seems to have a strong effect on how much the new hazard zones grow from the standard hazard zone areas. Hazards in rural environments display the largest area growth, and urban environments display the smallest area growth. Figure 38 shows the LS means plot. The Tukey test reveals that all three are significantly different. This result is not surprising, because rural environments typically have far less roads than urban or suburban environments. Hazard zones in rural environments were required to expand significantly farther to match nearby roads than hazard zones in more built-up environments.

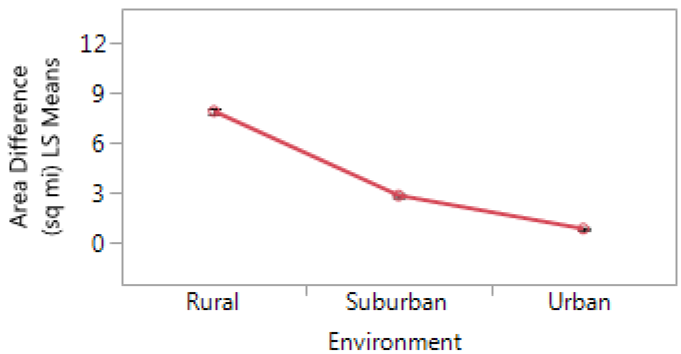

Figure 38: LS Means Plot of Environment for Area Difference ANOVA

The main effect of city also contributes to the area difference, but the effect appears to be smaller relative to environment and hazard. Houston and Chicago are not statistically different from each other, but both are statistically different from Denver. The LS means plot is shown in Figure 39. On average, hazard releases in Denver resulted in a larger expansion from the standard to new zone than in Houston or Chicago.

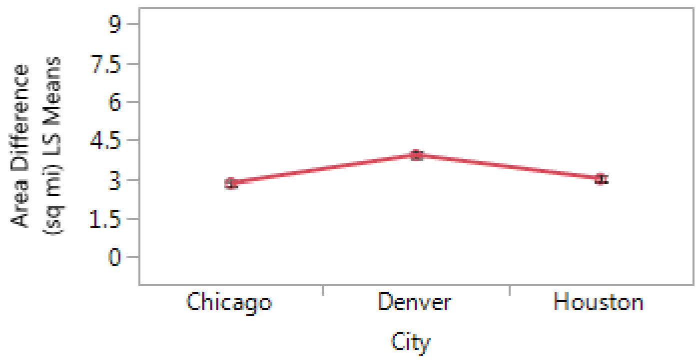

Figure 39: LS Means Plot of City for Area Difference ANOVA

As expected, the final main effect of hazard also shows a significant effect on the response of area difference. The LS means plot is shown in Figure 40. Tukey tests show that VX and anhydrous ammonia, which have the two smallest standard hazard distances, are not statistically different, but the rest of the hazards are distinct. Larger standard hazard zones are associated with larger area differences. City x Environment is the only interaction of notable interest. The LS means plot is shown in Figure 41. The plot shows that there is an interaction between cities and environments. For example, the rural Denver region displays a larger mean than the rural Chicago region, but the suburban Denver region has a smaller mean than the suburban Chicago region. There are many possible explanations for the presence of this interaction, such as politics, infrastructure, climate, economics, and terrain.

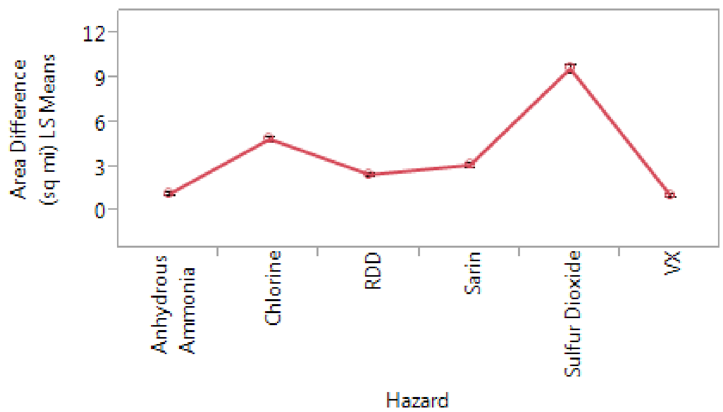

Figure 40: LS Means Plot of Hazard for Area Difference ANOVA

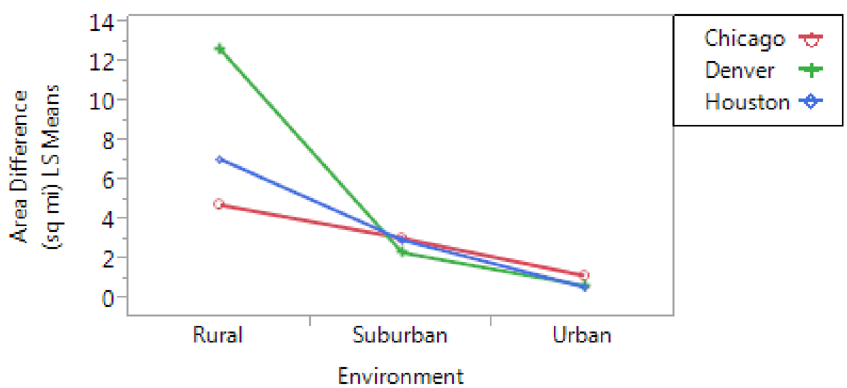

Figure 41: LS Means Plot of City x Environment for Area Difference ANOVA

Discussion

For both response variables (population and area difference), hazard, environment, and city were all significant effects. Hazard was expected to produce a significant effect, because the standard hazard distances vary across the six hazards. Environment exhibited strong, but different, effects on the response variables. City appeared to have a smaller, but still significant, effect on the response variables.

The environment had a discernable effect on the response variables. For population differences, rural regions showed the smallest values, and suburban regions showed the highest values. For area differences, rural regions showed the largest values, and urban regions showed the smallest values. This result makes sense, because rural areas have smaller populations and fewer physical boundaries, so the zones grew significantly to reach nearby boundaries, but still did not affect large numbers of people. Conversely, suburban regions have large residential populations and many roads, so the new zones tend to affect significantly more people even if they don't grow as much in area. Urban regions also have large populations, but often not as large as suburban regions, and urban regions often have even more roads in a grid layout. Environment also interacted significantly with both city and hazard. For population difference, no difference between cities in rural regions was found, whereas for area difference, the greatest variation between cities was found in rural regions. This suggests that population distributions in rural regions may be similar from one location to another, but the physical environment and layout of roads may differ based on local practices, policies, terrain, or other factors. Hazard made little difference in rural regions, but caused significant variation in suburban and urban regions. Because rural regions have fewer roads, the hazard zones generally have to expand farther. Thus, the amount of expansion is more robust against variations in input hazard distances. Comparatively, in urban and suburban regions, even slight differences in standard hazard zones may push the new hazard zones to different boundaries.

City also had a significant effect on the response variable, but this is likely due to underlying aspects of the cities studied, such as road network or population density. For population differences, Houston was associated with larger values, and Denver was associated with smaller values. While not tested across cities, this effect may be due to population density differences. All three cities have similar rural population densities, and there was no detectable difference in population growth across cities in rural regions. However, Houston has the largest suburban population and showed the highest population growth in suburban regions followed by Denver and then Chicago. Similarly, Chicago has the densest urban area and showed the most population growth in urban regions followed by Houston and then Denver. For area differences, Denver was associated with values larger than Chicago and Houston. This effect was pronounced for rural environments and practically non-existent for urban and suburban environments, which suggests that the main effect may be a function of regional rural road network differences. These differences across the three studied cities show that the behavior of expanding hazard zones is not always consistent between large U.S. cities and may depend on additional underlying variables.

Research Question 3

Is there a preferred set of physical boundaries that improves responder efficiency?

To answer Research Question 3, a select-the-best procedure was performed among the four new boundary sets with a goal to minimize the number of intersections. The number of intersections was used as a proxy variable for responder efficiency with the assumption that more intersections correlates to more complex cordons. The procedure was repeated including the standard hazard zone intersections for a total of five boundary sets. For the four boundary sets, the procedure was also conducted on each environment (urban, suburban, rural) subset. An indifference threshold of 15 intersections and an overall significance level of 0.05 were chosen as described in Chapter III. Additionally, a blocked ANOVA was used to analyze the data.

Select the Best

When comparing all five boundary sets, the select-the-best procedure found that the standard hazard zones have the fewest intersections. Because standard hazard zones do not conform to nearby physical boundaries, intersections for the standard hazard zones were determined using slightly different rules. Roads, rivers, and railroads that cross the cordons were counted. For the new hazard zones, which do conform to physical boundaries, every intersection was counted. This effectively includes roads, rivers, and railroads (using the appropriate combination for a given boundary set) that cross the cordon, as well as roads, rivers, and railroads that intersect along the cordon. Also, more intersections can be expected in the new zones, because the cordons were forced to incorporate physical boundaries, whereas the standard cordons were entirely independent from physical boundaries. Because of this difference in the specific measure used as intersections, this procedure was performed simply for purposes of general comparison. The means and standard deviations for each boundary set are shown in Table 21; the selected boundary set is highlighted.

Table 21: Number of Intersections by Boundary Set

	Standard Zones	Roads	Roads and Railroads	Roads and Rivers	Roads, Railroads, and Rivers
Mean Number of Intersections	64.81	162.3	158.9	151.6	150.0
Standard Deviation	82.97	160.3	157.4	149.9	149.1

When comparing only the four boundary sets applied to the new hazard zones, the select-the-best method found that using the combination of roads, railroads, and rivers (RRR) resulted in the fewest intersections or within 15 of the fewest intersections. A summary of the results is shown in Table 22, which follows the methodology and notation used in Chapter III. $W_{i,RRR}$ is the margin of error calculated for the RRR boundary set and the boundary set being compared. Each boundary set is compared to the boundary set with the lowest mean, so a compared boundary set must be sufficiently close to the RRR boundary set to be retained. The third row in Table 22 is the value compared against each boundary set's mean, where ϵ is the practical difference or indifference level and is set at 15 intersections. A value larger than the mean causes the boundary set to be rejected. Because the mean number of intersections is greater than the value calculated in the third row for each of the boundary sets, only the boundary set with the lowest mean number of intersections is retained and thus determined to be the best or near-best system. This system is the roads, railroads, and rivers boundary set.

Table 22: Select-the-Best

	Roads	**Roads and Railroads**	**Roads and Rivers**	**Roads, Railroads, and Rivers**
Mean Number of Intersections, Y_i	162.3	158.9	151.6	150.0
$W_{i,RRR}$	8.135	8.058	7.858	
$Y_{RRR} + \max\{0, W_{i,RRR} - \epsilon\}$	149.98	149.98	149.98	

The procedure was repeated for each environment. In the rural and suburban environments, the roads, railroads, and rivers boundary set was again selected as the best or near-best. In the urban environment, the select-the-best procedure could not determine whether the roads, railroads, and rivers boundary set or the roads and rivers boundary set was the best or near-best. The results are shown in Table 23, Table 24, and Table 25. The hazard zones in rural environments are associated with substantially fewer intersections than those in suburban and rural environments. This makes sense, because rural environments tend to have far less roads and railroads than urban and suburban environments.

Table 23: Select-the-Best (Rural)

	Roads	Roads and Railroads	Roads and Rivers	Roads, Railroads, and Rivers
Mean Number of Intersections	72.03	70.56	65.78	65.24
$\mathbf{W_{i,RRR}}$	5.732	5.643	5.163	
$\mathbf{Y_{RRR} + \max\{0, W_{i,RRR} - \epsilon\}}$	65.24	65.24	65.24	

Table 24: Select-the-Best (Suburban)

	Roads	Roads and Railroads	Roads and Rivers	Roads, Railroads, and Rivers
Mean Number of Intersections	206.3	199.5	183.7	180.2
$\mathbf{W_{i,RRR}}$	14.21	13.99	13.34	
$\mathbf{Y_{RRR} + \max\{0, W_{i,RRR} - \epsilon\}}$	180.2	180.2	180.2	

Table 25: Select-the-Best (Urban)

	Roads	Roads and Railroads	Roads and Rivers	Roads, Railroads, and Rivers
Mean Number of Intersections	208.5	206.6	205.2	204.5
$\mathbf{W_{i,RRR}}$	16.29	16.23	16.11	
$\mathbf{Y_{RRR} + \max\{0, W_{i,RRR} - \epsilon\}}$	205.8	205.7	205.6	

At a practical difference ϵ of 15, the rural and urban environments do not produce a significant difference between the boundary sets. The suburban environment results in a practically significant difference between the means of the first two and last two boundary sets, as shown in Table 24. In other words, within a suburban environment, there may be a meaningful improvement from the boundary sets of roads and roads/railroads to the boundary sets of roads/rivers and roads/railroads/rivers. If a practical difference of 0 is used instead of 15, the results change, indicating that there are some statistical differences that may not be practically significant. In the rural environment, only the roads boundary set is rejected. In the suburban environment, the best boundary set is determined to be either roads and rivers or roads, railroads, and rivers. In the urban environment, no boundary set can be confidently selected as best or near-best.

Blocked ANOVA

A blocked ANOVA was also run using the four boundary sets (i.e., roads; roads and railroads; roads and rivers; roads, railroads, and rivers) for the new hazard zones in order to reduce the variance due to the hazard and randomly generated spill point. The response variable was the number of intersections, and the factors were the boundary set and the scenario. A scenario is a combination of a single randomly generated release point and hazard. Four observations are associated with each scenario – one for each boundary set. This design in simulation means that each scenario is a block with four observations. The results are shown in Table 26, and the effect tests are shown in Table 27. The model has an R-squared of 0.9884, which is considerably larger than the unblocked ANOVA's R-squared of 0.0011, indicating that scenario does have a considerable effect on the number of intersections. The Tukey test for the blocked ANOVA reveals a statistically significant difference between each boundary set. The LS means plot is shown in Figure 42. However, the largest mean number of intersections (roads at 162) is within 15 of the smallest mean number of intersections (roads, railroads, and rivers at 150). Therefore, this research shows that the selection of a boundary set can influence the number of intersections, but the difference may not be large enough to be practically important.

Table 26: Blocked ANOVA for Intersections

Source	Degrees of Freedom	Sum of Squares	Mean Square	F Ratio	P-value
Model	5,942	559,498,707	94,160	256.18	< 0.0001
Error	17,817	6,548,743	367.6		
Total	23,759	566,047,450			

Table 27: Effect Tests for Blocked ANOVA

Source	Degrees of Freedom	Sum of Squares	F Ratio	P-value
Boundary Set	3	612,904	555.84	< 0.0001
Scenario	5,939	55,8885,802	256.03	< 0.0001

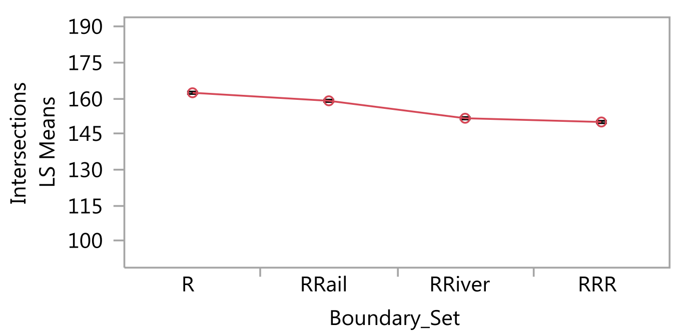

Figure 42: LS Means Plot for Intersections ANOVA

To verify the validity of the ANOVA, the assumptions of normality, constant variance, and independence were considered. The residuals fail the KSL goodness of fit test with a p-value of 0.01. However, like the ANOVAs in Research Question 2, the sample size is very large (23,760), so any deviation from normality is likely to result in a low p-value. The distribution of residuals (see Figure 43) shows a fairly normal appearance with a single, central peak. To check the assumption of constant variance, the residuals were plotted against the predicted values (see Figure 44). The scatter of points appears to be within a reasonable amount of variation to accept this condition. Finally, independence is satisfied by the design of the simulation. Scenarios are not expected to be independent from number of intersections, leading to the blocked design. Scenarios are independent, because the point locations were selected randomly. The ANOVA adequately meets the three assumptions to be considered statistically valid.

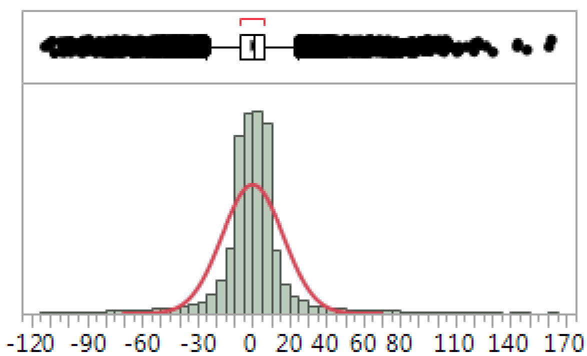

Figure 43: Distribution of Residuals for Intersections ANOVA

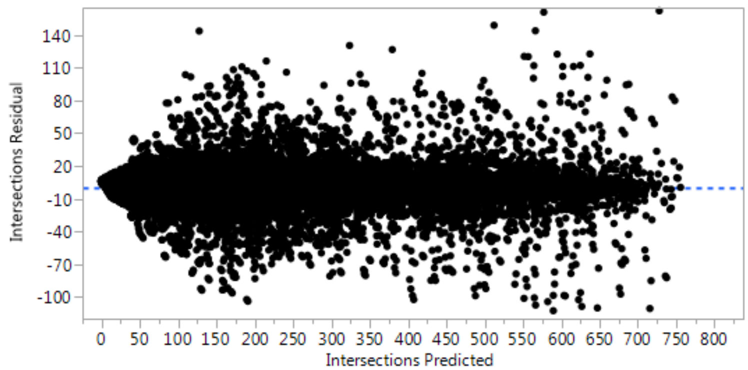

Figure 44: Residuals vs. Predicted for Intersections ANOVA

Discussion

Many factors can affect responder efficiency and will vary based on the conditions at any given incident site, so a proxy variable of number of intersections in the hazard cordon was used to represent efficiency consistently. Through a selection of the best method and blocked ANOVA, the boundary set using all three physical boundary types (roads, rivers, railroads) was determined to have the fewest intersections. The boundary set with roads and rivers was close to the lowest mean number of intersections, suggesting that rivers may be an important factor influencing the number of intersections. However, with a difference in means of less than 15 intersections between the highest and lowest means for all cases except suburban regions, the difference was not considered practically significant. This suggests that as long as responders use roads to establish boundaries, there is unlikely to be a significant increase or decrease in efficiency by selecting different boundaries to use. While there may exist a boundary set with a significantly lower number of intersections by using different boundary types not considered here, the choice between the four boundary sets used in this research is probably unimportant.

Summary

This chapter discussed the results of the research simulation by using the methodology described in the statistical analysis section of Chapter III. Confidence intervals and correlations revealed that paired differences for population and area, as well as percent changes, were statistically and practically significant. Depending on the specific hazard, median increases in population ranged from 342 to 8,073 people, and median increases in area ranged from 0.064 to 8.8 square miles. The correlations showed that larger standard hazard zones tend to increase the number of people and size of area affected more than small standard hazard zones. Conversely, smaller standard hazard zones tend to result in larger percent changes in population and area affected. Two ANOVAs explained the impact of rural, urban, or suburban environment, as well as city, on population and area differences. City, and especially environment, exhibited significant effects on how much the population and area changed with the new hazard zones. Rural regions generally displayed smaller population increases and larger area increases than urban and suburban regions. Additionally, several interactions between the effects of city, environment, and hazard were found to be of interest. A select-the-best procedure and a blocked ANOVA found statistically significant, but practically insignificant, differences among the four boundary sets used to generate new hazard zones. If roads are initially used to set up cordons, adding railroads and/or rivers to the cordon boundary makes little difference in the number of intersections that need to be controlled in the hazard zone boundary.

V. Conclusions and Recommendations

Chapter Overview

This research investigated and characterized initial emergency CBRN hazard zones in real world scenarios by accounting for the surrounding physical environment. These new hazard zones were matched to nearby roads, railroads, and rivers and then compared to the standard initial hazard zones as defined by the Emergency Response Guidebook (ERG) (DOT et al., 2012) for chemical accidents and attacks and Musolino et al. (2013) for radiological hazards. The comparison considered the population and area that would be affected by the hazard zones. Additionally, responder efficiency was compared across different combinations of physical boundaries. This chapter draws conclusions from the results of the research, discusses the significance of the research, acknowledges limitations, and provides recommendations for future research.

Conclusions of Research

This research is the first of its kind to evaluate the implications of expanding hazard zones to physical boundaries. Three research questions were answered to quantify the effects of expanding hazard zones to nearby physical boundaries, such as roads, railroads, and rivers. Standard hazard zones, as defined by the 2012 ERG (DOT et al.) and the recommendations from Musolino et al. (2013), were expanded until a complete cordon could be constructed using only roads, railroads, and rivers. By allowing the hazard zones to only expand, no additional risk was incurred by the population from the CBRN hazard. The study included six hazards and three cities to provide a range of data.

Anhydrous ammonia, chlorine, and sulfur dioxide represented the technological hazard as toxic inhalation hazards that are commonly used in industry and have historically been involved in releases that require an emergency response. VX, sarin, and RDDs represented the human-caused hazards as chemical warfare agents and radiological hazards that could be used in terrorism. Chicago, Denver, and Houston were selected as metropolitan areas that experience a high number of chemical incidents. To explore the effects of the type of environment on hazard zones, rural, suburban, and urban regions were selected for each of the three metropolitan areas. In total, nine regions and six hazards were evaluated. A simulation was developed using python and ArcGIS® to automate the creation of standard hazard zones and new hazard zones expanded to physical boundaries and to calculate the relevant statistics using a paired differences approach. The simulation randomly generated almost 1,000 points within the 9 regions. With 6 hazards at each point, almost 6,000 specific scenarios were generated. Additionally, responder efficiency was explored through a proxy variable that represents the complexity of the cordon. The number of intersections in the hazard zone cordons, defined as any connection between two or more physical boundaries at any point on the cordon, was counted. More intersections represent higher cordon complexity and a degradation to responder efficiency. The simulation was repeated at each scenario for each of four different boundary sets. The original boundary set used roads, railroads, and rivers. The additional boundary sets used roads only, roads and railroads, or roads and rivers. The simulation produced five output statistics relevant to the research: the difference in population affected by the new and standard hazard zones (where population data is sourced from U.S. Census Bureau data), the difference in area covered by the new and standard hazard zones, the percent population difference, the percent area difference, and the number of intersections in the cordon boundaries.

The data were first analyzed by constructing confidence intervals and examining correlations to determine how much the affected population and area increased for each of the six hazards. Each dataset using a different hazard showed a significant increase in the population affected, area affected, and percent changes in population and area. A general trend exists where hazards with larger standard distances result in greater absolute population and area increases, but smaller percent increases. For example, VX has the smallest standard hazard area at 0.064 square miles and had median increases from standard to new hazard zones of 342 people (445% change) and 0.6 square miles (884% change). Sulfur dioxide has the largest standard hazard area at approximately 23 square miles and had median increases of over 8,000 people (18.6% change) and 8.8 square miles (38.5% change). The other hazards (anhydrous ammonia, chlorine, sarin, and radiological dispersal devices) followed a similar trend. Furthermore, this relationship between standard hazard areas and response variables appears to follow a square root curve for population and area differences and a logarithmic curve for percent changes. Next, different environments and locations were considered to analyze their effects on hazard zones that are adapted to physical boundaries. Using the nine different regions across three cities and three environments, ANOVAs were conducted for population and area differences. Both environment and city had a significant effect. Rural regions tended to result in larger area differences, but smaller population differences than urban and suburban regions. The differences between the three cities were less substantial than those from the environment, but the differences still show that the particular city where an incident occurs can impact how big the hazard zones are and how many people are affected. Finally, four different physical boundaries were analyzed to determine if a particular combination of boundaries results in improved responder efficiency. The select-the-best procedure and blocked ANOVA found statistically significant, but practically insignificant, differences between the boundary sets. The boundary set using all the boundaries included in the research (roads, railroads, and rivers) had the fewest intersections, which is interpreted as the highest responder efficiency. However, this was only 12 intersections less than the boundary set with the most intersections – an 8% difference.

The results show that responders employing the method in this experiment to set up cordons will, on average, tend to experience a significant increase in population (340 to 8,000 more people, depending on hazard) and area (0.6 to 8.8 square miles) affected by their decisions. Because there is variation in the results, responders should expect to sometimes encounter situations without a significant increase in population or area, but sometimes deal with an extremely large and difficult to manage increase. The amount of increased impact also depends on the environment and city. Therefore, responders should also gather information about the specific location and be aware of the significant difference these characteristics can make. Based on this research, responders concerned about efficiency shouldn't dedicate resources to determining which boundary types to consider. There are likely more important considerations, such as the responder's preference, ease of designating and communicating specific boundaries for their particular community, and expected effort to maintain control over their resources.

Significance of Research

This research shows that hazard zones adapted to match physical boundaries are significantly different than the established hazard zone guidelines in terms of population affected and area covered. This finding has a number of implications. While the generated hazard zones matched to physical boundaries are not a perfect representation of reality, they are probably closer to reality than the simple circles and rectangles of the standard guidelines that do not account for the physical environment. The standard guidelines exist to be applicable in any environment, but implementation requires an additional step of adapting to the real world location. By incorporating some specific elements of the physical environment, this research produced hazard zones and data that may be more representative of the populations and areas impacted by a CBRN incident. If this methodology is incorporated into response modeling software, responders and researchers would have a model available that may more accurately reflects reality. Additionally, this study explicitly restricted hazard zones from shrinking. While it is possible that responders could choose to reduce hazard distances based on the specific scenario, the phenomenon of creeping conservatism indicates that responders and other decision makers are more likely to increase hazard distances when implementing cordons, evacuation orders, and shelter-in-place notices. It is important for responders, researchers, and community leaders to understand the effects of applying simple guidelines to real world situations, as well as complicating factors such as creeping conservatism and shadow evacuation, so that impacts to the local population and response agencies are not significantly under-estimated.

Additionally, the type of environment and even the specific city may affect the degree to which real world cordons differ from the standard guidelines. Rural environments tend to lead to particularly large zones, but may not impact that many more people. As urban and suburban environments are expanded to more realistic boundaries, the population affected can rapidly increase even if the total area is not much larger. The effects in rural regions do not depend on hazard, but in urban and suburban region, the hazard can make a significant difference in how large a cordon is and how many people will need to take protective action.

The size of hazard zones and the population within the hazard zones greatly influence a response effort. People within hazard zones must be notified of the incident and directed to take protective actions. Sheltering-in-place in particular requires continual communication with the population to provide appropriate updates throughout the incident duration. Evacuation orders should include routes and timing, as well as the defined area to be evacuated. As seen in Graniteville, SC, the more clearly the area can be communicated, the more likely the population is to comply (Mitchell et al, 2005). Hazard zones generated by this research may be easier to communicate, because they use easily defined boundaries. Also, more people evacuating increases the evacuation burden. This includes traffic congestion, time to evacuate, manpower to direct evacuees, mass care facilities and resources, and increased risk of evacuation-related accidents. The size of the hazard zone also impacts the response effort and the surrounding community. A larger hazard zone is typically harder to manage and requires more responders to establish and maintain. The hazard zone also affects the surrounding community, because access to that area is restricted. For example, through-traffic must be re-routed around the cordon.

For the responder concerned with efficiency of cordon set-up and control, this research suggests that the combination of physical boundaries used for hazard zones is usually not important. However, the experiment only considered roads, railroads, and rivers; other physical boundaries may enable or hinder efficiency.

The results of this thesis also have implications for the research community. Researchers seeking to evaluate effects of various CBRN scenarios tend to rely on hazard distance guidelines or plume modeling software. In reality, those zones do not account for the physical environment surrounding the incident site. Conclusions drawn and decisions made based on such hazard zones are limited by the assumption that the underlying environment doesn’t significantly affect the results. This research shows that surrounding physical boundaries can be a significant factor in the determining the effects of hazard zones.

Limitations of Research

Five limitations were noted in Chapter I. First, individual responders will often make different decisions about cordon set-up in the same situation based on their experiences, training, and judgments. Many factors influence incidents, and any of those factors can lead to different decisions, as well. Second, this research considered only six hazards and three cities to generate the data. Third, the ERG is mostly designed for accidental releases based on typical spill amounts and conditions, so worst-case scenarios might require larger hazard distances. The ERG similarly accounts for chemicals used as weapons by considering reasonable amounts and capabilities. Another limitation of the ERG is that the toxic inhalation hazards section used in this research to determine hazard distances only considers the airborne contamination and not environmental impacts of ground or water contamination. Fourth, only roads, railroads, and rivers were used as physical boundaries when many other possible physical boundaries exist in various locations. Fifth, populations were estimated using the U.S. Census Bureau's residential block counts, meaning that variation in the actual presence of people at the time of an incident is ignored.

Additionally, the GIS algorithm was limited by the road data obtained from the U.S. Census Bureau and U.S. Geological Survey. The data had an insufficient level of detail in the designations between types of roads to adequately distinguish between major roads, city roads, and minor roads such as alleys. With this additional detail, the algorithm could have been modified to use only certain types of roads.

Another limitation of the research is due to the algorithm itself. The code requires the new hazard zones to expand until a complete polygon consisting of roads, railroads, and rivers can be drawn. This can be problematic for release points near large open areas without those boundaries. For example, Lake Michigan is a very large open area near Chicago. To avoid this problem consistently, the program restricted the use of points that would cause an expansion into the lake.

Recommendations for Future Research

There are ample opportunities for further research related to this thesis. Addressing the limitations would allow for additional conclusions to be drawn. If type of road can be distinguished to a sufficient level of detail, then the algorithm could be refined to target the roads more likely to be used as cordon boundaries. Additionally, varying options could be provided to allow for different rules to be applied; for example, all roads, only major roads, or a specific subset of roads could be selected. Greater options in physical boundaries would also allow for further comparisons to be conducted regarding responder efficiency.

This research found some relationships between the hazard type, environment, and city. The experiment could be replicated for more and different areas, with different hazards, and/or in different types of environments. Additional factors, such as terrain, weather patterns over time, varying wind speeds, population density, and road network characteristics, could also be added.

Another opportunity for further research is the development of a field-ready tool for responders. The algorithm could be further refined to allow for more options, the ability to easily make adjustments to the recommended cordon boundaries based on responder judgment, and the integration with other incident management information. For example, this research required cordons to exactly match physical boundaries; the field-ready tool could present the automatically generated zones on a local map and then allow the responder to decide to cut across an open field on one side of the zone instead. A small city or Department of Defense installation may serve as a good case study environment to research and test this type of emergency response tool. An Air Force installation in particular has generally consistent and clearly defined roles, responsibilities, authorities, and protocols that might build a framework for such a tool.

This study investigated responder efficiency with a simple, single parameter, proxy variable. In reality, other factors influence the efficiency of a response effort, such as available manpower and equipment, time of day and year, location, support agreements, and the quality of plans and checklists. Further research could explore other potential elements of responder efficiency, develop a method to measure those elements, and maximize or balance overall efficiency of incident scene management.

To better capture the number of people directly impacted by CBRN hazard zones, the actual population present in the area could be estimated. The researcher could account for different areas (residential, industrial, offices, retail, recreational, transportation, etc.), times of day or night, days of the week, and seasons. This would provide further insight into the true impact of an event and may more accurately represent differences in environment (rural, suburban, and urban).

Many factors influence responder decisions throughout an incident, including the initial phase and cordon set-up stage. Further research could identify and characterize these factors. This would enable the development of more realistic models and decision-support tools for the responder and researcher. Inquiries regarding which factors are most influential or how to optimize the cordon set-up process could be investigated.

Summary

This research enhanced understanding of initial response operations to a CBRNE incident by investigating and characterizing how initial hazard zones change in a real world environment that accounts for physical boundaries. Background information provided the motivation and research questions for the research effort. Next, a literature review informed and framed the research questions and methodology. To explore how hazard zones change when adapted to nearby physical boundaries in a variety of locations and for six different hazards, a simulation collected data through the generation and calculation of standard and new hazard zones. The analysis of the results revealed significant differences in the population and area affected by new hazard zones compared to standard hazard zones, as well as significant effects of the specific environment and city where the hazard was located. Additionally, the particular combination of physical boundaries used in creating hazard zones was not found to influence responder efficiency. Finally, this chapter provided a brief review of the research and its conclusions, the significance of the results, limitations of the study, and several suggestions for future research.

Appendix A: Python Scripts for Simulation

A1. Data Initialization

```
# ---------------------------------------------------------------------------
# GIS_data_setup.py
# Micki Sundheim
# Updated on: 2015-12-29
# Description: set up GIS shapefiles: census block data, Roads, RRiver, RRail, RRR
# ---------------------------------------------------------------------------

import arcpy
import sys

## USER INPUT VARIABLES
gdb_name = 'TX'
box = "box"  #regions in which random points will be generated
clipper = "Clipper"  #large polygon around general area of interest
box_Buffer = "box_Buffer"  #smaller polygon(s) around more specific area of interest

## DEFINE WORKSPACE
arcpy.env.workspace = "folder\\" + str(gdb_name) + "ThesisGDB.gdb"  #insert folder location
GDB = "folder\\"+str(gdb_name)+"ThesisGDB.gdb"  #insert folder location

# Input versions of boundary data from Census Bureau, USGS, etc.
pop = "pop"
Roads = "Roads_Clip"
Rail = "Rail"
River = "River"

# Clipped versions 1
pop_clipper = "pop_clipper"
Roads_clipper = "Roads_clipper"
Rail_clipper = "Rail_clipper"
River_clipper = "River_clipper"

# Projected versions
pop_Clip_Proj = "pop_Clip_Proj"  #final census data for use in code_summary_loop
Roads_Proj = "Roads_Proj"
Rail_Proj = "Rail_Proj"
River_Proj = "River_Proj"

# Clipped versions 2
Roads_Proj_Clip = "Roads_Proj_Clip"
Rail_Proj_Clip = "Rail_Proj_Clip"
River_Proj_Clip = "River_Proj_Clip"

# Merged versions
RRail_Proj_Clip = "RRail_Proj_Clip"
RRiver_Proj_Clip = "RRiver_Proj_Clip"
RRR_Proj_Clip = "RRR_Proj_Clip"

# Lined versions, final for use in code_summary_loop
```

```
Roads_Proj_Line_Clip = "Roads_Proj_Line_Clip"
RRailLine = "RRailLine"
RRiverLine = "RRiverLine"
RRRLine = "RRRLine"


# CLIP TO CLIPPER
arcpy.Clip_analysis(pop, clipper, pop_clipper, "")
arcpy.Clip_analysis(Roads, clipper, Roads_clipper, "")
arcpy.Clip_analysis(Rail, clipper, Rail_clipper, "")
arcpy.Clip_analysis(River, clipper, River_clipper, "")
print("clipped to Clipper")

# ENSURE CONSISTENT PROJECTIONS
spatialRef = arcpy.Describe(box).spatialReference

arcpy.Project_management(pop_clipper, pop_Clip_Proj, spatialRef)
arcpy.Project_management(Roads_clipper, Roads_Proj, spatialRef)
arcpy.Project_management(Rail_clipper, Rail_Proj, spatialRef)
arcpy.Project_management(River_clipper, River_Proj, spatialRef)
print("Projected")

# CLIP TO BOX_BUFFER
arcpy.Clip_analysis(Roads_Proj, box_Buffer, Roads_Proj_Clip, "")
arcpy.Clip_analysis(Rail_Proj, box_Buffer, Rail_Proj_Clip, "")
arcpy.Clip_analysis(River_Proj, box_Buffer, River_Proj_Clip, "")
print("clipped to box_Buffer")

# MERGE
arcpy.Merge_management([Roads_Proj_Clip, Rail_Proj_Clip], RRail_Proj_Clip)
arcpy.Merge_management([Roads_Proj_Clip, River_Proj_Clip], RRiver_Proj_Clip)
arcpy.Merge_management([Roads_Proj_Clip, River_Proj_Clip, Rail_Proj_Clip], RRR_Proj_Clip)
print("Merged")

# LINE - BREAK LINES AT EVERY INTERSECTION
arcpy.FeatureToLine_management(Roads_Proj_Clip, Roads_Proj_Clip_Line)
print("Roads Lined")
arcpy.FeatureToLine_management(RRail_Proj_Clip, RRailLine)
print("RRail Lined")
arcpy.FeatureToLine_management(RRiver_Proj_Clip, RRiverLine)
print("RRiver Lined")
arcpy.FeatureToLine_management(RRR_Proj_Clip, RRRLine)
print("RRR Lined")
```

A2. Overall Script

```
# ---------------------------------------------------------------------------
# code_summary_loop.py
# Micki Sundheim
# Updated on: 2016-1-1
# Description: Generate hazard zones and calculate area and population affected

# Requires module hazardzonesm.py
# ---------------------------------------------------------------------------

import arcpy
import math
import numpy
import random
import sys

import hazardzonesm

## USER INPUT VARIABLES
#wdir = 45  #Chicago
wdir = 0   #Denver
#wdir = 315 #Houston
loc = 'Denver'  #city name
wdir = int(wdir)
numpoints = 50  #number of random points to be generated per region
min = 0  #minimum distance between random points
mindist = str(min) + " Meters" #add units

gdb_name = 'CO'  #State designation

## DEFINE WORKSPACE
arcpy.env.workspace = "folder\\" + str(gdb_name) + "ThesisGDB.gdb" #input folder location
GDB = "folder\\"+str(gdb_name)+"ThesisGDB.gdb"  #input folder location

# DEFINE VARIABLES
box = "box"
spills = "CO_spills"
name = str(spills)
pop_Clip_Proj = "pop_Clip_Proj"

Spill_Location_Buffer3 = "Spill_Location_Buffer3"
Clip_IsoZone = "Clip_IsoZone"
Downwind_Zone = "Downwind_Zone"
Downwind_Zone_dissolve = "Downwind_Zone_dissolve"
eraseDZone = "eraseDZone"
Clip_DZone = "Clip_DZone"
Clip_DZone_Statistics = "Clip_DZone_Statistics"
Clip_IsoZone_Stats = "Clip_IsoZone_Stats"
Stats = "Statistics_" + str(loc)

RoadsLine = "Roads_Proj_Line_Clip"
RoadsRailLine = "RRailLine"
RoadsRiverLine = "RRiverLine"
RRRLine = "RRRLine"

```

```
NewIsoZone = "New_IsoZone"
NewIsoZone_whole = "NewIsoZone_whole"
Isovert = "Isovert"
poly = "All_Polygons"
dpoly = "All_DPolygons"
New_eraseDZone = "New_eraseDZone"
New_eraseDZone_whole = "New_eraseDZone_whole"
Dvert = "Dvert"
Clip_NewIsoZone = "Clip_NewIsoZone"
Clip_NewDZone = "Clip_NewDZone"
New_Stats = "Statistics_NewZone_" + str(loc)
NewDZone_Stats = "NewDZone_Stats"

spatialRef = arcpy.Describe(box).spatialReference

# DELETE STUFF
if arcpy.Exists(spills):
    arcpy.Delete_management(spills)
if arcpy.Exists(Spill_Location_Buffer3):
    arcpy.Delete_management(Spill_Location_Buffer3)
if arcpy.Exists(Clip_IsoZone):
    arcpy.Delete_management(Clip_IsoZone)
if arcpy.Exists(Downwind_Zone):
    arcpy.Delete_management(Downwind_Zone)
if arcpy.Exists(Downwind_Zone_dissolve):
    arcpy.Delete_management(Downwind_Zone_dissolve)
if arcpy.Exists(eraseDZone):
    arcpy.Delete_management(eraseDZone)
if arcpy.Exists(Clip_DZone):
    arcpy.Delete_management(Clip_DZone)
if arcpy.Exists(Clip_IsoZone_Stats):
    arcpy.Delete_management(Clip_IsoZone_Stats)
if arcpy.Exists(Clip_DZone_Statistics):
    arcpy.Delete_management(Clip_DZone_Statistics)
if arcpy.Exists(Stats):
    arcpy.Delete_management(Stats)

if arcpy.Exists(NewIsoZone):
    arcpy.Delete_management(NewIsoZone)
if arcpy.Exists(NewIsoZone_whole):
    arcpy.Delete_management(NewIsoZone_whole)
if arcpy.Exists(Isovert):
    arcpy.Delete_management(Isovert)
if arcpy.Exists(poly):
    arcpy.Delete_management(poly)
if arcpy.Exists(Clip_NewIsoZone):
    arcpy.Delete_management(Clip_NewIsoZone)
if arcpy.Exists(dpoly):
    arcpy.Delete_management(dpoly)
if arcpy.Exists(Clip_NewDZone):
    arcpy.Delete_management(Clip_NewDZone)
if arcpy.Exists(New_eraseDZone):
    arcpy.Delete_management(New_eraseDZone)
if arcpy.Exists(New_eraseDZone_whole):
    arcpy.Delete_management(New_eraseDZone_whole)
if arcpy.Exists(Dvert):
    arcpy.Delete_management(Dvert)
if arcpy.Exists(New_Stats):
    arcpy.Delete_management(New_Stats)
```

```
if arcpy.Exists(NewDZone_Stats):
    arcpy.Delete_management(NewDZone_Stats)


# DEFINE HAZARD DISTANCES
#assign hazards to number
H = {'Anhydrous Ammonia':0, 'Chlorine':1, 'Sulfur_Dioxide':2, 'VX':3, 'GB':4, 'RDD':5}

#define hazard distances
Iso_dist = [125, 1000, 1000, 60, 400, 250]
DW_dist = [500, 3500, 7600, 400, 2100, 2000]

# GENERATE RANDOM POINTS WITHIN BOX
hazardzonesm.randompts(box, numpoints, GDB, spatialRef, min, name)
print('points created')

# ADD XY GEOMETRY TO ATTRIBUTE TABLE OF SPILLS
arcpy.AddXY_management(spills)

# ADD ORIGINAL SHAPE AREAS TO CENSUS DATA
#Add Field to store original shape areas
arcpy.AddField_management(pop_Clip_Proj, "Orig_Area2", "FLOAT", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")

#Calculate Field of original shape areas
arcpy.CalculateField_management(pop_Clip_Proj, "Orig_Area2", "[Shape_area]", "VB", "")

# CREATE TABLE TO STORE STATISTICS
arcpy.CreateTable_management(GDB, Stats)
arcpy.AddField_management(Stats, "FREQUENCY", "LONG")
arcpy.AddField_management(Stats, "SUM_Pop_Affected", "DOUBLE")
arcpy.AddField_management(Stats, "SUM_Area_Affected", "DOUBLE")
arcpy.AddField_management(Stats, "Hazard", "TEXT", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
arcpy.AddField_management(Stats, "Zone", "TEXT", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
arcpy.AddField_management(Stats, "Std_New", "TEXT", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
arcpy.AddField_management(Stats, "Environment", "INTEGER", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
arcpy.AddField_management(Stats, "City", "TEXT", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
arcpy.AddField_management(Stats, "Point_num", "INTEGER", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
arcpy.AddField_management(Stats, "Vertices", "INTEGER", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
arcpy.AddField_management(Stats, "Boundary_Set", "TEXT", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
arcpy.AddField_management(Stats, "Pop_diff", "DOUBLE", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
arcpy.AddField_management(Stats, "Area_diff", "DOUBLE", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
arcpy.AddField_management(Stats, "Pop_diff_per", "DOUBLE", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
arcpy.AddField_management(Stats, "Area_diff_per", "DOUBLE", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")

```

```python
print('Stats table created')
lost = 0
lost_pt = []
lost_hz = []

## FOR EACH HAZARD:
i = 0
while i < 6:
    print('Hazard: ' + str(i))

    #assign appropriate distance variables
    isodist = Iso_dist[i]
    dist = DW_dist[i]

    ## FOR EACH POINT:
    points = arcpy.SearchCursor(spills)
    for point in points:

        p = point.OBJECTID
        envir = point.PolygonOID
        print('Hazard: ' + str(i))
        print('point: ' + str(p))

        # MAKE FEATURE LAYER
        arcpy.MakeFeatureLayer_management(spills, "spills_lyr")
        # SELECT POINT IN POINTS
        arcpy.SelectLayerByAttribute_management("spills_lyr","NEW_SELECTION", '"OBJECTID" = %d' % point.OBJECTID)

        # BUFFER AND CLIP INITIAL ISOLATION ZONE
        #Buffer for initial isolation zone at hazard distance
        arcpy.Buffer_analysis("spills_lyr", Spill_Location_Buffer3, isodist, "FULL", "ROUND", "NONE", "")

        #Clip block data by isolation zone
        arcpy.Clip_analysis(pop_Clip_Proj, Spill_Location_Buffer3, Clip_IsoZone, "")

        Bound = 'NA'  #Standard zones

        # Count the lines intersecting the IsoZone
        arcpy.MakeFeatureLayer_management(RRRLine, "bound_lyr")
        arcpy.SelectLayerByLocation_management("bound_lyr", "CROSSED_BY_THE_OUTLINE_OF", Spill_Location_Buffer3, "", "NEW_SELECTION")
        isovert1 = int(arcpy.GetCount_management("bound_lyr").getOutput(0))

        # ADD POPULATION AND AREA DATA, CALCULATE SUMMARY STATISTICS AND PUT IN TABLE
        hazardzonesm.stats(Clip_IsoZone, Clip_IsoZone_Stats, 'Initial Isolation', Stats, i, loc, 'Standard', envir, p, isovert1, Bound)

        #Append to stats table
        arcpy.Append_management(Clip_IsoZone_Stats, Stats)

        sc = arcpy.da.SearchCursor(Clip_IsoZone_Stats, ['SUM_Pop_Affected', 'SUM_Area_Affected'])
        for row in sc:
            isopop1 = row[0]
            isoarea1 = row[1]
```

```
        arcpy.Delete_management(Clip_IsoZone_Stats)
        del sc

        # CREATE FEATURE CLASS FOR DOWNWIND ZONE
        arcpy.CreateFeatureclass_management(GDB, "Downwind_Zone", "POLYGON", spills, "DISABLED", "DISABLED", spatialRef, "", "0", "0", "0")

        # MAKE DOWNWIND ZONE
        #Read point geometry of spill location, create rectangle, create extra buffer if RDD, erase initial isolation area
        hazardzonesm.rectangle("spills_lyr", dist, isodist, wdir, spatialRef, i, Downwind_Zone, Spill_Location_Buffer3, eraseDZone, Clip_IsoZone, Downwind_Zone_dissolve)

        # CLIP CENSUS DATA WITH DOWNWIND ZONE
        #Clip rectangle to get census block layer within downwind-only zone
        arcpy.Clip_analysis(pop_Clip_Proj, eraseDZone, Clip_DZone, "")

        # Count the lines that intersect the zone
        arcpy.SelectLayerByLocation_management("bound_lyr", "CROSSED_BY_THE_OUTLINE_OF", eraseDZone, "", "NEW_SELECTION")
        arcpy.SelectLayerByLocation_management("bound_lyr", "CROSSED_BY_THE_OUTLINE_OF", Spill_Location_Buffer3, "", "REMOVE_FROM_SELECTION")
        dvert1 = int(arcpy.GetCount_management("bound_lyr").getOutput(0))
        vert = isovert1 + dvert1  #add initial isolation and protection action intersections

        # ADD POPULATION AND AREA DATA, CALCULATE SUMMARY STATISTICS AND PUT IN TABLE*
        hazardzonesm.stats(Clip_DZone, Clip_DZone_Statistics, 'Protective Action', Stats, i, loc, 'Standard', envir, p, vert, Bound)

        #Append to stats table
        arcpy.Append_management(Clip_DZone_Statistics, Stats)

        sc = arcpy.da.SearchCursor(Clip_DZone_Statistics, ['SUM_Pop_Affected', 'SUM_Area_Affected'])
        for row in sc:
            dpop1 = row[0]
            darea1 = row[1]

        arcpy.Delete_management(Clip_DZone_Statistics)
        del sc

        ##########################
        # NEW HAZARD ZONES MATCHED TO PHYSICAL BOUNDARIES #
        b=0
        while b < 4:   #for each boundary set

            #Use the associated boundary set shapefile
            if b == 0:
                Bounds = RoadsLine
                Bound = 'R'
            elif b == 1:
                Bounds = RoadsRailLine
                Bound = 'RRail'
            elif b == 2:
                Bounds = RoadsRiverLine
```

```
                Bound = 'RRiver'
            else:
                Bounds = RRRLine
                Bound = 'RRR'

            # Make feature layers, select by location the lines around standard initial iso zone
            arcpy.MakeFeatureLayer_management(Bounds, "road_lyr")
            arcpy.MakeFeatureLayer_management(Spill_Location_Buffer3, "buff_lyr")

            distance = 15000 # distance for buffer to select
            unit = str(distance) + " Meters" #add units

            # Select Layer By Location - lines that surround the standard zone
            arcpy.SelectLayerByLocation_management("road_lyr", "WITHIN_A_DISTANCE", "buff_lyr", unit, "NEW_SELECTION")
            arcpy.SelectLayerByLocation_management("road_lyr", "CROSSED_BY_THE_OUTLINE_OF", "buff_lyr","", "REMOVE_FROM_SELECTION")
            arcpy.SelectLayerByLocation_management("road_lyr", "WITHIN", "buff_lyr","", "REMOVE_FROM_SELECTION")

            # Turn everything into polygons
            arcpy.FeatureToPolygon_management("road_lyr", poly)
            arcpy.MakeFeatureLayer_management(poly, "poly_lyr")

            # Select the feature that contains the buffer
            arcpy.SelectLayerByLocation_management("poly_lyr", "CONTAINS", "buff_lyr","", "NEW_SELECTION")

            # Eliminate holes
            arcpy.EliminatePolygonPart_management("poly_lyr", NewIsoZone_whole, "PERCENT", "0 SquareMeters", "99", "ANY")

            # Count the intersections
            arcpy.SelectLayerByLocation_management("road_lyr", "SHARE_A_LINE_SEGMENT_WITH", NewIsoZone_whole, "", "NEW_SELECTION")
            isovert = int(arcpy.GetCount_management("road_lyr").getOutput(0))

            # Clip block data by new isolation zone
            arcpy.Clip_analysis(pop_Clip_Proj, NewIsoZone_whole, Clip_NewIsoZone, "")

            # ADD POPULATION AND AREA DATA, CALCULATE SUMMARY STATISTICS AND PUT IN TABLE
            hazardzonesm.stats(Clip_NewIsoZone, New_Stats, 'Initial Isolation', Stats, i, loc, 'New', envir, p, isovert, Bound)

            #Append to stats table
            arcpy.Append_management(New_Stats, Stats)

            sc = arcpy.da.SearchCursor(New_Stats, ['SUM_Pop_Affected', 'SUM_Area_Affected'])
            for row in sc:
                isopop2 = row[0]
                isoarea2 = row[1]

            arcpy.Delete_management(New_Stats)
            del sc
```

```
            ## NEW DOWNWIND ZONE ##

            # Make feature layer, select by location around downwind zone
            arcpy.MakeFeatureLayer_management(eraseDZone, "dbuff_lyr")

            distance = 15000 # distance for buffer to select
            unit = str(distance) + " Meters" #add units

            # Select Layer By Location - lines that surround the standard zone
            arcpy.SelectLayerByLocation_management("road_lyr", "WITHIN_A_DISTANCE", "dbuff_lyr", unit, "NEW_SELECTION")
            arcpy.SelectLayerByLocation_management("road_lyr", "CROSSED_BY_THE_OUTLINE_OF", "dbuff_lyr","", "REMOVE_FROM_SELECTION")
            arcpy.SelectLayerByLocation_management("road_lyr", "WITHIN", "dbuff_lyr","", "REMOVE_FROM_SELECTION")

            # Turn everything into polygons
            arcpy.FeatureToPolygon_management("road_lyr", dpoly)
            arcpy.MakeFeatureLayer_management(dpoly, "dpoly_lyr")

            # Select the feature that contains the downwind zone
            arcpy.SelectLayerByLocation_management("dpoly_lyr", "CONTAINS", "dbuff_lyr","", "NEW_SELECTION")

            # Eliminate holes
            arcpy.EliminatePolygonPart_management("dpoly_lyr", New_eraseDZone, "PERCENT", "0 SquareMeters", "99", "ANY")

            # Check if New_eraseDZone has any features
            k = 0
            with arcpy.da.SearchCursor(New_eraseDZone, ['Orig_FID']) as sc:
                for row in sc:
                    k = k + 1   #count rows
            del sc

            if k == 0:          #if no rows, then try again with bigger buffer
                arcpy.Delete_management("dbuff_lyr")
                arcpy.Delete_management("dpoly_lyr")
                arcpy.Delete_management(New_eraseDZone)
                arcpy.Delete_management(dpoly)

                lost = lost + 1      #track info about lost PAZs
                lost_pt.append(p)
                lost_hz.append(i)

                arcpy.MakeFeatureLayer_management(eraseDZone, "dbuff_lyr")

                distance = 40000 # extra distance for buffer to select
                unit = str(distance) + " Meters" #add units

                # Select Layer By Location - lines that surround the standard zone
                arcpy.SelectLayerByLocation_management("road_lyr", "WITHIN_A_DISTANCE", "dbuff_lyr", unit, "NEW_SELECTION")
                arcpy.SelectLayerByLocation_management("road_lyr", "CROSSED_BY_THE_OUTLINE_OF", "dbuff_lyr","", "REMOVE_FROM_SELECTION")
                arcpy.SelectLayerByLocation_management("road_lyr", "WITHIN", "dbuff_lyr","", "REMOVE_FROM_SELECTION")
```

```
                # Turn everything into polygons
                arcpy.FeatureToPolygon_management("road_lyr", dpoly)
                arcpy.MakeFeatureLayer_management(dpoly, "dpoly_lyr")

                # Select the feature that contains the downwind zone
                arcpy.SelectLayerByLocation_management("dpoly_lyr", "CONTAINS", "dbuff_lyr","", "NEW_SELECTION")

                # Eliminate holes
                arcpy.EliminatePolygonPart_management("dpoly_lyr", New_eraseDZone, "PERCENT", "0 SquareMeters", "99", "ANY")

            # Subtract area in isolation zone that overlaps with downwind area
            arcpy.Erase_analysis(New_eraseDZone, Clip_NewIsoZone, New_eraseDZone_whole)

            # Count the intersections
            arcpy.SelectLayerByLocation_management("road_lyr", "SHARE_A_LINE_SEGMENT_WITH", New_eraseDZone_whole, "", "NEW_SELECTION")
            arcpy.SelectLayerByLocation_management("road_lyr", "SHARE_A_LINE_SEGMENT_WITH", NewIsoZone_whole, "", "REMOVE_FROM_SELECTION")
            dvert = int(arcpy.GetCount_management("road_lyr").getOutput(0))
            vert = isovert + dvert  #Add new iso and protective action intersections

            # Clip census data by new protective action zone
            arcpy.Clip_analysis(pop_Clip_Proj, New_eraseDZone_whole, Clip_NewDZone, "")

            # ADD POPULATION AND AREA DATA, CALCULATE SUMMARY STATISTICS AND PUT IN TABLE
            hazardzonesm.stats(Clip_NewDZone, NewDZone_Stats, 'Protective Action', Stats, i, loc, 'New', envir, p, vert, Bound)

            # Read area and pop values from NewDZone_Stats if they exist
            j = 0
            with arcpy.da.SearchCursor(NewDZone_Stats, ['SUM_Pop_Affected', 'SUM_Area_Affected']) as sc:
                for row in sc:
                    dpop2 = row[0]
                    darea2 = row[1]
                    j = j + 1   #count rows

            if j == 0:          #if no rows, then add data
                dpop2 = 0       #assign dpop2 and darea2 as zero
                darea2 = 0

                fields = ['FREQUENCY','SUM_Pop_Affected','SUM_Area_Affected','Hazard','Zone','Std_New','Environment','City','Point_num','Vertices','Boundary_Set',
                          'Pop_diff','Area_diff','Pop_diff_per','Area_diff_per']

                Incur = arcpy.da.InsertCursor(NewDZone_Stats, fields)   #insert row with variables and 0s for pop and area
                popdiff = math.ceil(isopop2 - (dpop1+isopop1))  #round up to nearest integer
                areadiff = isoarea2 - (darea1+isoarea1)
```

```
                pop_per = ((isopop2 - (dpop1+isopop1))/(dpop1+isopop1+1)) * 100  #calculate population percent difference
                if darea1+isoarea1 == 0:  #double check to avoid dividing by zero
                    areaper = -2
                else:
                    areaper = ((isoarea2 - (darea1+isoarea1))/(darea1+isoarea1)) * 100  #calculate area percent difference

                #Insert new row with data
                newrow = [0,0,0,str(i),'Protective Action','New',envir,loc,p,isovert,Bound,popdiff,areadiff,pop_per,areaper]
                Incur.insertRow(newrow)

                del Incur

            elif j > 0:     #if row exists in NewDZone_Stats:

                pop_per = ((dpop2+isopop2 - (dpop1+isopop1))/(dpop1+isopop1+1)) * 100  #calculate pop percent difference
                if darea1+isoarea1 == 0:
                    areaper = -2
                elif darea1+isoarea1 > 0:
                    areaper = ((darea2+isoarea2 - (darea1+isoarea1))/(darea1+isoarea1)) * 100  #calculate area percent difference

                #Update table with stats
                Upcur = arcpy.da.UpdateCursor(NewDZone_Stats, ['Pop_diff','Area_diff','Pop_diff_per','Area_diff_per', 'Vertices'])
                for row in Upcur:
                    row[0] = math.ceil(dpop2+isopop2 - (dpop1+isopop1))
                    row[1] = darea2+isoarea2 - (darea1+isoarea1)
                    row[2] = pop_per
                    row[3] = areaper
                    row[4] = isovert + dvert
                    Upcur.updateRow(row)
                del Upcur

            #Append to stats table
            arcpy.Append_management(NewDZone_Stats, Stats)

            #clean up variables

            arcpy.Delete_management(NewDZone_Stats)
            isopop2 = 0
            isoarea2 = 0
            dpop2 = 0
            darea2 = 0
            popdiff = 0
            areadiff = 0
            pop_per = 0
            areaper = 0

            isovert = 0
            dvert = 0
            vert = 0
```

```

            arcpy.Delete_management(NewIsoZone)
            arcpy.Delete_management(NewIsoZone_whole)
            arcpy.Delete_management(Isovert)
            arcpy.Delete_management(poly)
            arcpy.Delete_management(dpoly)
            arcpy.Delete_management(New_eraseDZone)
            arcpy.Delete_management(New_eraseDZone_whole)
            arcpy.Delete_management(Dvert)
            arcpy.Delete_management(Clip_NewIsoZone)
            arcpy.Delete_management(Clip_NewDZone)

            arcpy.Delete_management("road_lyr")
            arcpy.Delete_management("buff_lyr")
            arcpy.Delete_management("poly_lyr")
            arcpy.Delete_management("dbuff_lyr")
            arcpy.Delete_management("dpoly_lyr")
            arcpy.Delete_management("bound_lyr")

            b = b + 1  #next boundary set
            print('Bound: ' + Bound)

        # DELETE STUFF TO REUSE VARIABLES ON EVERY LOOP

        arcpy.Delete_management(Spill_Location_Buffer3)
        arcpy.Delete_management(Clip_IsoZone)
        arcpy.Delete_management(Downwind_Zone)
        arcpy.Delete_management(eraseDZone)
        arcpy.Delete_management(Clip_DZone)

        isopop1 = 0
        isoarea1 = 0
        dpop1 = 0
        darea1 = 0
        isovert1 = 0
        dvert1 = 0

    del points
    del point

    i = i + 1  #next hazard

#end while

print(lost)
print(lost_pt)
print(lost_hz)
```

A3. Hazard Zones Module

```python
# ---------------------------------------------------------------------------
# hazardzonesm.py
# Micki Sundheim
# Updated on: 2015-12-20
# Description: Module for use with code_summary_loop
# Three functions defined: stats (calculate/add statistics), rectangle (create downwind zone), randompts (generate random points)
# ---------------------------------------------------------------------------

import arcpy
import math
import numpy
import random
import sys

#########################
# ADD POP AND AREA DATA
def stats(zoneclip, table, zone, Stats, i, city, stdnew, envir, ptnum, vert, bound):

    # Add Fields for population and area affected by incident
    arcpy.AddField_management(zoneclip, "Pop_Affected", "FLOAT", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
    arcpy.AddField_management(zoneclip, "Area_Affected", "FLOAT", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")

    # Calculate Field of population by ratios of area affected for each census block
    arcpy.CalculateField_management(zoneclip, "Pop_Affected", "[POP10]* [Shape_area]/ [Orig_Area2]", "VB", "")

    # Calculate Field for area affected
    arcpy.CalculateField_management(zoneclip, "Area_Affected", "!shape.area@squaremeters!", "PYTHON", "")

    ##CALCULATE STATS AND PUT IN TABLE
    # Summary Statistics - sum total population and areas affected
    arcpy.Statistics_analysis(zoneclip, table, "Pop_Affected SUM;Area_Affected SUM", "")
    # Add Fields for hazard and zone type and other info
    arcpy.AddField_management(table, "Hazard", "TEXT", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
    arcpy.AddField_management(table, "Zone", "TEXT", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
    arcpy.AddField_management(table, "Std_New", "TEXT", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
    arcpy.AddField_management(table, "Environment", "INTEGER", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
    arcpy.AddField_management(table, "City", "TEXT", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
    arcpy.AddField_management(table, "Point_num", "INTEGER", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
    arcpy.AddField_management(table, "Vertices", "INTEGER", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
    arcpy.AddField_management(table, "Boundary_Set", "TEXT", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
```

```
    arcpy.AddField_management(table, "Pop_diff", "DOUBLE", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
    arcpy.AddField_management(table, "Area_diff", "DOUBLE", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
    arcpy.AddField_management(table, "Pop_diff_per", "DOUBLE", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
    arcpy.AddField_management(table, "Area_diff_per", "DOUBLE", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")

    # Fill in new fields
    fields = ["Hazard","Zone","Std_New","Environment","City","Point_num","Vertices","Boundary_Set","Pop_diff","Area_diff"]
    Upcur = arcpy.da.UpdateCursor(table, fields)
    for row in Upcur:

        row[0] = str(i)
        row[1] = zone
        row[2] = stdnew
        row[3] = envir
        row[4] = city
        row[5] = ptnum
        row[6] = vert
        row[7] = bound

        #Insert place holders for pop and area diff
        if stdnew == 'New':
            if zone == 'Protective Action':
                row[8] = 0
                row[9] = 0

            else:
                row[8] = -1
                row[9] = -1

        else:
            row[8] = -1
            row[9] = -1

        Upcur.updateRow(row)
    del Upcur

    print(stdnew + ' ' + zone + " zone complete")
    arcpy.AddMessage(stdnew + ' ' + zone + ' zone complete')

    return

###################
# CREATE DOWNWIND ZONE
def rectangle(Spill_Location, dist, isodist, wdir, spatialRef, i, Downwind_Zone, Spill_Location_Buffer3, eraseDZone, Clip_IsoZone, Downwind_Zone_dissolve):

    # Read point geometry of Spill_Location
    rows = arcpy.SearchCursor(Spill_Location)
    for row in rows:
        spillx = row.getValue("POINT_X")
        spilly = row.getValue("POINT_Y")
    del row, rows

    # Define coordinates of rectangle zone about origin
```

```
    theta = (wdir - 90) * math.pi/180

    # If RDD, calculate different rectangle
    if i == 5:
        #top left
        topl = numpy.array([[0], [dist/4], [1]])
        #top right
        topr = numpy.array([[dist], [dist/4], [1]])
        #bottom left
        botl = numpy.array([[0], [-dist/4], [1]])
        #bottom right
        botr = numpy.array([[dist], [-dist/4], [1]])

    # For the rest of the hazards:
    else:
        topl = numpy.array([[0], [dist/2], [1]])
        topr = numpy.array([[dist], [dist/2], [1]])
        botl = numpy.array([[0], [-dist/2], [1]])
        botr = numpy.array([[dist], [-dist/2], [1]])

    # Rotate coordinates by wind direction
    R = numpy.array([[math.cos(theta), math.sin(theta), spillx], [-math.sin(theta), math.cos(theta), spilly]])  #rotation matrix
    topl = numpy.dot(R,topl)  #top left
    topr = numpy.dot(R,topr)  #top right
    botl = numpy.dot(R,botl)  #bottom left
    botr = numpy.dot(R,botr)  #bottom right

    # Make a new empty array
    array = arcpy.Array()

    # Make coordinates points
    point1 = arcpy.Point(float(topl[0]), float(topl[1]))
    point2 = arcpy.Point(float(topr[0]), float(topr[1]))
    point3 = arcpy.Point(float(botr[0]), float(botr[1]))
    point4 = arcpy.Point(float(botl[0]), float(botl[1]))

    # Put the points in the array
    array.add(point1)
    array.add(point2)
    array.add(point3)
    array.add(point4)

    # Make a polygon out of the array
    rectangle = arcpy.Polygon(array, spatialRef)
    cursor = arcpy.da.InsertCursor(Downwind_Zone, ["SHAPE@"])
    cursor.insertRow([rectangle])

    # Add extra buffer around hot zone for RDD
    if i == 5:
        pntGeom = arcpy.PointGeometry(arcpy.Point(spillx, spilly)) #center of circle
        circle = pntGeom.buffer(isodist * 2)
        cursor.insertRow([circle])
        del cursor
        arcpy.Dissolve_management(Downwind_Zone, Downwind_Zone_dissolve) #dissolve buffer and downwind zones
        #subtract area in hot zone: erase
```

```
        arcpy.Erase_analysis(Downwind_Zone_dissolve, Spill_Location_Buffer3, eraseDZone)
        arcpy.Delete_management(Downwind_Zone_dissolve)
    else:
        del cursor
        #subtract area in isolation zone: erase
        arcpy.Erase_analysis(Downwind_Zone, Spill_Location_Buffer3, eraseDZone)

    # Clean stuff up to reuse feature layers and tables
    arcpy.Delete_management("spills_lyr")

    del R, array

    return

########################
# GENERATE RANDOM POINTS IN POLYGONS
# Adapted from Ian Broad, http://ianbroad.com/arcgis-toolbox-generate-random-points-arcpy/
def randompts(box, numpoints, GDB, spatialRef, min, name):

    # Determine number of polygons in box feature class (number of regions)
    result = arcpy.GetCount_management(box)
    features = int(result.getOutput(0))

    # Initialize counter values
    attempts = 1000
    keep_attempts = 'NO'

    # Create point feature class for spill locations
    spills = arcpy.CreateFeatureclass_management(GDB, str(name), "POINT", "", "DISABLED", "DISABLED", spatialRef)
    arcpy.AddField_management(spills, "PolygonOID", "TEXT")

    # Read extent of box
    fields = ["SHAPE@", "OID@"]
    with arcpy.da.SearchCursor(box, (fields)) as rows:
        for row in rows:
            oid = row[1]
            polygon_geom = row[0]
            distance = []

            xmin, xmax= row[0].extent.XMin, row[0].extent.XMax
            ymin, ymax = row[0].extent.YMin, row[0].extent.YMax

            i = 0
            attempt = 1

            # Create random points
            with arcpy.da.InsertCursor(spills, ("SHAPE@", "PolygonOID")) as insert:

                while i < numpoints:  #for i number of points
                    xcoord = random.uniform(xmin, xmax)
                    ycoord = random.uniform(ymin, ymax)

                    point = arcpy.Point(xcoord, ycoord)  #create point from coordinates
```

```
                    point_geom = arcpy.PointGeometry(point, polygon_geom.spatialReference)
                    contains_point = polygon_geom.contains(point_geom)  #check if point is within polygon box

                    if attempt < attempts:  #control number of attempts in case conditions can't be met
                        if contains_point == True and i == 0:  #put first good point in feature class
                            distance.append(point_geom)
                            insert.insertRow((point_geom, oid))
                            i = i + 1

                        elif contains_point == True and i > 0:  #subsequent points in box
                            distance_check = True
                            for point in distance:  #check minimum distance criterion against each existing point
                                if point_geom.distanceTo(point) > min:
                                    pass
                                else:  #if doesn't pass distance criterion, then increment attempt
                                    distance_check = False
                                    attempt = attempt + 1

                            if distance_check == True:  #if point passes distance criteria for all existing points, then add to feature class
                                distance.append(point_geom)
                                insert.insertRow((point_geom, oid))
                                i = i + 1

                    #if attempts exceeded, then break while loop and print error message
                    else:
                        print('Failed attempting to generate {0} random points for Polygon OID: {1}'.format(attempts, oid))
                        print('Decrease number of random points or the minimum distance and try again.')
                        arcpy.AddError("Failed attempting to generate {0} random points for Polygon OID: {1}".format(attempts, oid))
                        arcpy.AddError("Decrease number of random points or the minimum distance and try again.")
                        i = numpoints

    return
```

Appendix B: Python Script for Custom ArcGIS® Tool

```
# --------------------------------------------------------------------------
# code_summary_loop_Tool.py
# Micki Sundheim
# Updated on: 2015-2-11
# Description: Custom ArcGIS tool to generate hazard zones and calculate area and population affected for a specific incident
# Requires module hazardzonesm.py
# Tool must also be set up in ArcMap to use script
# --------------------------------------------------------------------------

import arcpy
import math
import numpy
import random
import sys

import hazardzonesm

## USER INPUT VARIABLES: hazard types, wind direction, name of city, save location, spill location, census data
# User must have/create shapefile with spill location, population shapefile, roads/etc. shapefile
hazard = arcpy.GetParameterAsText(0)
wdir = arcpy.GetParameterAsText(1)
loc = arcpy.GetParameterAsText(2)
wdir = int(wdir)
#gdb_name = arcpy.GetParameterAsText(3)
GDB = arcpy.GetParameterAsText(3)
spills = arcpy.GetParameterAsText(4)
pop_Clip_Proj = arcpy.GetParameterAsText(5)
RRRLine = arcpy.GetParameterAsText(6)

## DEFINE WORKSPACE
arcpy.env.workspace = GDB  #input folder location
#GDB = "folder\\"+str(gdb_name)+"ThesisGDB.gdb"  #input folder location

# DEFINE VARIABLES
Spill_Location_Buffer3 = "Spill_Location_Buffer3"
Clip_IsoZone = "Clip_IsoZone"
Downwind_Zone = "Downwind_Zone"
Downwind_Zone_dissolve = "Downwind_Zone_dissolve"
eraseDZone = "eraseDZone"
Clip_DZone = "Clip_DZone"
Clip_DZone_Statistics = "Clip_DZone_Statistics"
Clip_IsoZone_Stats = "Clip_IsoZone_Stats"
Stats = "ToolStatistics_" + str(loc)

NewIsoZone = "New_IsoZone"
NewIsoZone_whole = "NewIsoZone_whole"
Isovert = "Isovert"
poly = "All_Polygons"
dpoly = "All_DPolygons"
New_eraseDZone = "New_eraseDZone"
New_eraseDZone_whole = "New_eraseDZone_whole"
Dvert = "Dvert"
Clip_NewIsoZone = "Clip_NewIsoZone"
```

```
Clip_NewDZone = "Clip_NewDZone"
New_Stats = "Statistics_NewZone_" + str(loc)
NewDZone_Stats = "NewDZone_Stats"

spatialRef = arcpy.Describe(spills).spatialReference

# DELETE STUFF
if arcpy.Exists(Spill_Location_Buffer3):
    arcpy.Delete_management(Spill_Location_Buffer3)
if arcpy.Exists(Clip_IsoZone):
    arcpy.Delete_management(Clip_IsoZone)
if arcpy.Exists(Downwind_Zone):
    arcpy.Delete_management(Downwind_Zone)
if arcpy.Exists(Downwind_Zone_dissolve):
    arcpy.Delete_management(Downwind_Zone_dissolve)
if arcpy.Exists(eraseDZone):
    arcpy.Delete_management(eraseDZone)
if arcpy.Exists(Clip_DZone):
    arcpy.Delete_management(Clip_DZone)
if arcpy.Exists(Clip_IsoZone_Stats):
    arcpy.Delete_management(Clip_IsoZone_Stats)
if arcpy.Exists(Clip_DZone_Statistics):
    arcpy.Delete_management(Clip_DZone_Statistics)
if arcpy.Exists(Stats):
    arcpy.Delete_management(Stats)
if arcpy.Exists(Stats):
    arcpy.Delete_management(Stats)

if arcpy.Exists(NewIsoZone):
    arcpy.Delete_management(NewIsoZone)
if arcpy.Exists(NewIsoZone_whole):
    arcpy.Delete_management(NewIsoZone_whole)
if arcpy.Exists(Isovert):
    arcpy.Delete_management(Isovert)
if arcpy.Exists(poly):
    arcpy.Delete_management(poly)
if arcpy.Exists(Clip_NewIsoZone):
    arcpy.Delete_management(Clip_NewIsoZone)
if arcpy.Exists(dpoly):
    arcpy.Delete_management(dpoly)
if arcpy.Exists(Clip_NewDZone):
    arcpy.Delete_management(Clip_NewDZone)
if arcpy.Exists(New_eraseDZone):
    arcpy.Delete_management(New_eraseDZone)
if arcpy.Exists(New_eraseDZone_whole):
    arcpy.Delete_management(New_eraseDZone_whole)
if arcpy.Exists(Dvert):
    arcpy.Delete_management(Dvert)
if arcpy.Exists(New_Stats):
    arcpy.Delete_management(New_Stats)
if arcpy.Exists(NewDZone_Stats):
    arcpy.Delete_management(NewDZone_Stats)

# DEFINE HAZARD DISTANCES
#assign hazards to number
H = {'Anhydrous Ammonia':0, 'Chlorine':1, 'Sulfur Dioxide':2, 'VX':3, 'GB':4, 'RDD':5}

#define hazard distances
```

```
Iso_dist = [125, 1000, 1000, 60, 400, 250]
DW_dist = [300, 2900, 5100, 300, 4900, 2000]

#assign appropriate distance variables
i = H[hazard]
isodist = Iso_dist[i]
dist = DW_dist[i]
arcpy.AddMessage('Hazard: ' + str(hazard) + "\n" 'Initial Isolation Distance: ' + str(isodist) + ' meters' + "\n" 'Protective Action Distance: ' + str(dist) + ' meters')

# ADD XY GEOMETRY TO ATTRIBUTE TABLE OF SPILL_LOCATION
arcpy.AddXY_management(spills)

# ADD ORIGINAL SHAPE AREAS TO CENSUS DATA
#Add Field to store original shape areas
arcpy.AddField_management(pop_Clip_Proj, "Orig_Area2", "FLOAT", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")

#Calculate Field of original shape areas
arcpy.CalculateField_management(pop_Clip_Proj, "Orig_Area2", "[Shape_area]", "VB", "")

# CREATE TABLE TO STORE STATISTICS
arcpy.CreateTable_management(GDB, Stats)
arcpy.AddField_management(Stats, "FREQUENCY", "LONG")
arcpy.AddField_management(Stats, "SUM_Pop_Affected", "DOUBLE")
arcpy.AddField_management(Stats, "SUM_Area_Affected", "DOUBLE")
arcpy.AddField_management(Stats, "Hazard", "TEXT", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
arcpy.AddField_management(Stats, "Zone", "TEXT", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
arcpy.AddField_management(Stats, "Std_New", "TEXT", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
arcpy.AddField_management(Stats, "Environment", "INTEGER", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
arcpy.AddField_management(Stats, "City", "TEXT", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
arcpy.AddField_management(Stats, "Point_num", "INTEGER", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
arcpy.AddField_management(Stats, "Vertices", "INTEGER", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
arcpy.AddField_management(Stats, "Boundary_Set", "TEXT", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
arcpy.AddField_management(Stats, "Pop_diff", "DOUBLE", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
arcpy.AddField_management(Stats, "Area_diff", "DOUBLE", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
arcpy.AddField_management(Stats, "Pop_diff_per", "DOUBLE", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")
arcpy.AddField_management(Stats, "Area_diff_per", "DOUBLE", "", "", "", "", "NULLABLE", "NON_REQUIRED", "")

arcpy.AddMessage('Stats table created')

lost = 0
lost_pt = []
lost_hz = []

```

```
isopop2 = 0
isoarea2 = 0
dpop2 = 0
darea2 = 0
popdiff = 0
areadiff = 0
pop_per = 0
areaper = 0

isovert = 0
dvert = 0
vert = 0

isopop1 = 0
isoarea1 = 0
dpop1 = 0
darea1 = 0
isovert1 = 0
dvert1 = 0

## FOR SPILL POINT:
points = arcpy.SearchCursor(spills)
for point in points:

    p = point.OBJECTID
    envir = 0

    # MAKE FEATURE LAYER
    arcpy.MakeFeatureLayer_management(spills, "spills_lyr")
    # SELECT POINT IN POINTS
    arcpy.SelectLayerByAttribute_management("spills_lyr","NEW_SELECTION", '"OBJECTID" = %d' % point.OBJECTID)

    # BUFFER AND CLIP INITIAL ISOLATION ZONE
    #Buffer for initial isolation zone at distance in spill location attribute table
    arcpy.Buffer_analysis("spills_lyr", Spill_Location_Buffer3, isodist, "FULL", "ROUND", "NONE", "")

    #Clip block data by isolation zone
    arcpy.Clip_analysis(pop_Clip_Proj, Spill_Location_Buffer3, Clip_IsoZone, "")

    Bound = 'NA'

    # Count the lines intersecting the IsoZone
    arcpy.MakeFeatureLayer_management(RRRLine, "bound_lyr")
    arcpy.SelectLayerByLocation_management("bound_lyr", "CROSSED_BY_THE_OUTLINE_OF", Spill_Location_Buffer3, "", "NEW_SELECTION")
    isovert1 = int(arcpy.GetCount_management("bound_lyr").getOutput(0))

    # ADD POPULATION AND AREA DATA, CALCULATE SUMMARY STATISTICS AND PUT IN TABLE*
    hazardzonesm.stats(Clip_IsoZone, Clip_IsoZone_Stats, 'Initial Isolation', Stats, i, loc, 'Standard', envir, p, isovert1, Bound)

    #append to stats table
    arcpy.Append_management(Clip_IsoZone_Stats, Stats)

```

```
    sc = arcpy.da.SearchCursor(Clip_IsoZone_Stats, ['SUM_Pop_Affected', 'SUM_Area_Affected'])
    for row in sc:
        isopop1 = row[0]
        isoarea1 = row[1]

    arcpy.Delete_management(Clip_IsoZone_Stats)
    del sc

    # CREATE FEATURE CLASS FOR DOWNWIND ZONE
    arcpy.CreateFeatureclass_management(GDB, "Downwind_Zone", "POLYGON", spills, "DISABLED", "DISABLED", spatialRef, "", "0", "0", "0")

    # MAKE DOWNWIND ZONE
    #read point geometry of spill location, create rectangle, create extra buffer if RDD, erase initial isolation area**
    hazardzonesm.rectangle("spills_lyr", dist, isodist, wdir, spatialRef, i, Downwind_Zone, Spill_Location_Buffer3, eraseDZone, Clip_IsoZone, Downwind_Zone_dissolve)

    # CLIP CENSUS DATA WITH DOWNWIND ZONE**
    #clip rectangle to get census block layer within downwind-only zone
    arcpy.Clip_analysis(pop_Clip_Proj, eraseDZone, Clip_DZone, "")

    # Count the lines that intersect the zone
    arcpy.SelectLayerByLocation_management("bound_lyr", "CROSSED_BY_THE_OUTLINE_OF", eraseDZone, "", "NEW_SELECTION")
    arcpy.SelectLayerByLocation_management("bound_lyr", "CROSSED_BY_THE_OUTLINE_OF", Spill_Location_Buffer3, "", "REMOVE_FROM_SELECTION")
    dvert1 = int(arcpy.GetCount_management("bound_lyr").getOutput(0))
    vert = isovert1 + dvert1  #add initial isolation and protection action intersections

    # ADD POPULATION AND AREA DATA, CALCULATE SUMMARY STATISTICS AND PUT IN TABLE*
    hazardzonesm.stats(Clip_DZone, Clip_DZone_Statistics, 'Protective Action', Stats, i, loc, 'Standard', envir, p, vert, Bound)

    #append to stats table
    arcpy.Append_management(Clip_DZone_Statistics, Stats)

    sc = arcpy.da.SearchCursor(Clip_DZone_Statistics, ['SUM_Pop_Affected', 'SUM_Area_Affected'])
    for row in sc:
        dpop1 = row[0]
        darea1 = row[1]

    arcpy.Delete_management(Clip_DZone_Statistics)
    del sc

    ##########################
    # NEW HAZARD ZONES MATCHED TO PHYSICAL BOUNDARIES #
    Bounds = RRRLine
    Bound = 'User Input'

    # Make feature layers, select by location the lines around standard initial iso zone
    arcpy.MakeFeatureLayer_management(Bounds, "road_lyr")
    arcpy.MakeFeatureLayer_management(Spill_Location_Buffer3, "buff_lyr")
```

```
    distance = 15000 # distance for buffer to select
    unit = str(distance) + " Meters" #add units

    # Select Layer By Location - lines that cross the boundary of the circle buffer
    arcpy.SelectLayerByLocation_management("road_lyr", "WITHIN_A_DISTANCE", "buff_lyr", unit, "NEW_SELECTION")
    arcpy.SelectLayerByLocation_management("road_lyr", "CROSSED_BY_THE_OUTLINE_OF", "buff_lyr","", "REMOVE_FROM_SELECTION")
    arcpy.SelectLayerByLocation_management("road_lyr", "WITHIN", "buff_lyr","", "REMOVE_FROM_SELECTION")

    # Turn everything into polygons
    arcpy.FeatureToPolygon_management("road_lyr", poly)
    arcpy.MakeFeatureLayer_management(poly, "poly_lyr")

    # Select the feature that contains the buffer
    arcpy.SelectLayerByLocation_management("poly_lyr", "CONTAINS", "buff_lyr","", "NEW_SELECTION")

    # Eliminate holes
    arcpy.EliminatePolygonPart_management("poly_lyr", NewIsoZone_whole, "PERCENT", "0 SquareMeters", "99", "ANY")

    # Count the intersections
    arcpy.SelectLayerByLocation_management("road_lyr", "SHARE_A_LINE_SEGMENT_WITH", NewIsoZone_whole, "", "NEW_SELECTION")
    isovert = int(arcpy.GetCount_management("road_lyr").getOutput(0))

    # Clip block data by new isolation zone
    arcpy.Clip_analysis(pop_Clip_Proj, NewIsoZone_whole, Clip_NewIsoZone, "")

    # ADD POPULATION AND AREA DATA, CALCULATE SUMMARY STATISTICS AND PUT IN TABLE*
    hazardzonesm.stats(Clip_NewIsoZone, New_Stats, 'Initial Isolation', Stats, i, loc, 'New', envir, p, vert, Bound)

    #append to stats table
    arcpy.Append_management(New_Stats, Stats)

    sc = arcpy.da.SearchCursor(New_Stats, ['SUM_Pop_Affected', 'SUM_Area_Affected'])
    for row in sc:
        isopop2 = row[0]
        isoarea2 = row[1]

    arcpy.Delete_management(New_Stats)
    del sc

    ## NEW DOWNWIND ZONE ##

    # Make feature layer, select by location around downwind zone
    arcpy.MakeFeatureLayer_management(eraseDZone, "dbuff_lyr")

    distance = 15000 # distance for buffer to select
    unit = str(distance) + " Meters" #add units

    # Select Layer By Location - lines that surround the standard zone
```

```python
    arcpy.SelectLayerByLocation_management("road_lyr", "WITHIN_A_DISTANCE", "dbuff_lyr", unit, "NEW_SELECTION")
    arcpy.SelectLayerByLocation_management("road_lyr", "CROSSED_BY_THE_OUTLINE_OF", "dbuff_lyr","", "REMOVE_FROM_SELECTION")
    arcpy.SelectLayerByLocation_management("road_lyr", "WITHIN", "dbuff_lyr","", "REMOVE_FROM_SELECTION")

    # Turn everything into polygons
    arcpy.FeatureToPolygon_management("road_lyr", dpoly)
    arcpy.MakeFeatureLayer_management(dpoly, "dpoly_lyr")

    # Select the feature that contains the downwind zone
    arcpy.SelectLayerByLocation_management("dpoly_lyr", "CONTAINS", "dbuff_lyr", "", "NEW_SELECTION")

    # Eliminate holes
    arcpy.EliminatePolygonPart_management("dpoly_lyr", New_eraseDZone, "PERCENT", "0 SquareMeters", "99", "ANY")

    # Check if New_eraseDZone has any features
    k = 0
    with arcpy.da.SearchCursor(New_eraseDZone, ['Orig_FID']) as sc:
        for row in sc:
            k = k + 1   #count rows
    del sc

    if k == 0:          #if no rows, then try again with bigger buffer
        arcpy.Delete_management("dbuff_lyr")
        arcpy.Delete_management("dpoly_lyr")
        arcpy.Delete_management(New_eraseDZone)
        arcpy.Delete_management(dpoly)

        lost = lost + 1      #track info about lost PAZs
        lost_pt.append(p)
        lost_hz.append(i)

        arcpy.MakeFeatureLayer_management(eraseDZone, "dbuff_lyr")

        distance = 40000 # extra distance for buffer to select
        unit = str(distance) + " Meters" #add units

        # Select Layer By Location - lines that surround the standard zone
        arcpy.SelectLayerByLocation_management("road_lyr", "WITHIN_A_DISTANCE", "dbuff_lyr", unit, "NEW_SELECTION")
        arcpy.SelectLayerByLocation_management("road_lyr", "CROSSED_BY_THE_OUTLINE_OF", "dbuff_lyr","", "REMOVE_FROM_SELECTION")
        arcpy.SelectLayerByLocation_management("road_lyr", "WITHIN", "dbuff_lyr","", "REMOVE_FROM_SELECTION")

        # Turn everything into polygons
        arcpy.FeatureToPolygon_management("road_lyr", dpoly)
        arcpy.MakeFeatureLayer_management(dpoly, "dpoly_lyr")

        # Select the feature that contains the downwind zone
        arcpy.SelectLayerByLocation_management("dpoly_lyr", "CONTAINS", "dbuff_lyr","", "NEW_SELECTION")

        # Eliminate holes
```

```
        arcpy.EliminatePolygonPart_management("dpoly_lyr", New_eraseDZone, "PERCENT", "0 SquareMeters", "99", "ANY")

    # Subtract area in isolation zone that overlaps with downwind area
    arcpy.Erase_analysis(New_eraseDZone, Clip_NewIsoZone, New_eraseDZone_whole)

    # Count the intersections
    arcpy.SelectLayerByLocation_management("road_lyr", "SHARE_A_LINE_SEGMENT_WITH", New_eraseDZone_whole, "", "NEW_SELECTION")
    arcpy.SelectLayerByLocation_management("road_lyr", "SHARE_A_LINE_SEGMENT_WITH", NewIsoZone_whole, "", "REMOVE_FROM_SELECTION")
    dvert = int(arcpy.GetCount_management("road_lyr").getOutput(0))
    vert = isovert + dvert  #Add new iso and protective action intersections

    # Clip census data by new protective action zone
    arcpy.Clip_analysis(pop_Clip_Proj, New_eraseDZone_whole, Clip_NewDZone, "")

    # ADD POPULATION AND AREA DATA, CALCULATE SUMMARY STATISTICS AND PUT IN TABLE*
    hazardzonesm.stats(Clip_NewDZone, NewDZone_Stats, 'Protective Action', Stats, i, loc, 'New', envir, p, vert, Bound)

    # Read area and pop values from NewDZone_Stats if they exist
    j = 0
    with arcpy.da.SearchCursor(NewDZone_Stats, ['SUM_Pop_Affected', 'SUM_Area_Affected']) as sc:
        for row in sc:
            dpop2 = row[0]
            darea2 = row[1]
            j = j + 1   #count rows

    if j == 0:          #if no rows, then add data
        dpop2 = 0       #assign dpop2 and darea2 as zero
        darea2 = 0

        fields = ['FREQUENCY','SUM_Pop_Affected','SUM_Area_Affected','Hazard','Zone','Std_New','Environment','City','Point_num','Vertices','Boundary_Set',
                  'Pop_diff','Area_diff','Pop_diff_per','Area_diff_per']
        Incur = arcpy.da.InsertCursor(NewDZone_Stats, fields)   #insert row with variables and 0s for pop and area
        popdiff = math.ceil(isopop2 - (dpop1+isopop1))  #round up to nearest integer
        areadiff = isoarea2 - (darea1+isoarea1)
        pop_per = ((isopop2 - (dpop1+isopop1))/(dpop1+isopop1+1)) * 100  #calculate population percent difference

        if darea1+isoarea1 == 0:
            areaper = -2
        else:
            areaper = ((isoarea2 - (darea1+isoarea1))/(darea1+isoarea1)) * 100  #calculate area percent difference

        #Insert new row with data
        newrow = [0,0,0,str(i),'Protective Action','New',envir,loc,p,isovert,Bound,popdiff,areadiff,pop_per,areaper]
```

```
        Incur.insertRow(newrow)
        del Incur

    elif j > 0:     #if row exists in NewDZone_Stats:

        pop_per = ((dpop2+isopop2 - (dpop1+isopop1))/(dpop1+isopop1+1)) * 100  #calculate pop percent difference
        if darea1+isoarea1 == 0:
            areaper = -2
        elif darea1+isoarea1 > 0:
            areaper = ((darea2+isoarea2 - (darea1+isoarea1))/(darea1+isoarea1)) * 100  #calculate area percent difference

        #Update table with stats
        Upcur = arcpy.da.UpdateCursor(NewDZone_Stats, ['Pop_diff','Area_diff','Pop_diff_per','Area_diff_per', 'Vertices'])
        for row in Upcur:
            row[0] = math.ceil(dpop2+isopop2 - (dpop1+isopop1))
            row[1] = darea2+isoarea2 - (darea1+isoarea1)
            row[2] = pop_per
            row[3] = areaper
            row[4] = isovert + dvert
            Upcur.updateRow(row)
        del Upcur

    #append to stats table
    arcpy.Append_management(NewDZone_Stats, Stats)

    #clean up variables
    arcpy.Delete_management(NewDZone_Stats)

del points
del point

arcpy.AddMessage(lost)
arcpy.AddMessage(lost_pt)
arcpy.AddMessage(lost_hz)
arcpy.AddMessage("\n" + 'Population Affected by Standard Zones: ' + str(round(math.ceil(isopop1 + dpop1))))
arcpy.AddMessage('Area Affected by Standard Zones: ' + str(round(((isoarea1 + darea1)* 3.86102e-7),2)) + ' square miles')
arcpy.AddMessage('Population Affected by New Zones: ' + str(round(math.ceil(isopop2 + dpop2))))
arcpy.AddMessage('Area Affected by New Zones: ' + str(round(((isoarea2 + darea2) * 3.86102e-7),2)) + ' square miles' + "\n")
```

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14. ABSTRACT
In the United States, industrial and terrorist use of chemical, biological, radiological, and nuclear (CBRN) materials pose a risk to public safety. During the initial phase of typical CBRN incidents, emergency responders establish hazard zones based on standard distances from published guidelines and recommendations. This research investigates how standard hazard zones change in a real world environment that accounts for physical boundaries. Using a python simulation in ArcGIS®, new hazard zones were created by expanding standard hazard zones to follow nearby roads, railroads, and rivers. The new and standard zones were compared by calculating the population and area affected by each zone. Additionally, responder efficiency was compared across different combinations of physical boundaries. The simulation generated 990 random points across three cities and three environments (urban, suburban, rural) and was replicated for six hazards. The results revealed significantly larger populations and areas affected by new zones compared to standard zones and significant effects from the environment and city where the incident occurred. Depending on hazard, the median growth ranged from approximately 340 to 8,000 people and 0.6 to 8.8 square miles. The particular combination of physical boundaries used in creating hazard zones was not found to influence responder efficiency.

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