Using GIS to Perform a Risk Assessment for Air-Transmitted Bioterrorism within San Diego County

by

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To my fiancé as well as my family for the continuous patience and support throughout my aspirations.

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Acknowledgements

I am grateful for my professors throughout my education who have both inspired me and guided me through many ideas or journeys, as well as family for their sacrifice, patience, guidance, and support.

List of Abbreviations

GIS	Geographic information system
GISci	Geographic information science
SSI	Spatial Sciences Institute
USC	University of Southern California
CDC	Center for Disease Control
BTRA	Biological Threat Risk Assessment
MSA	Metropolitan Statistical Area
DHS	Department of Homeland Security
NREL	National Renewable Energy Laboratory
RDWTI	RAND Database of Worldwide Terrorist Incidents
GTD	Global Terrorism Database

Abstract

With continuous advances in science and technology, there is high potential for a variety of agents to be used in bioterrorist attacks, making it difficult to prevent and mitigate the effects. Geographic Information Science (GIS) is an important tool in contributing to the preparedness, response, and recovery from bioterrorist attacks. GIS is beneficial in processing a significant amount of data for a multifactorial analysis and generating visual representations that indicate risk levels of designated areas, dependent upon specific variables throughout the area. Authorities such as health and human service agencies, Center for Disease Control (CDC), and the Department of Homeland Security (DHS) could utilize this information to decrease the effect of the attack and increase mitigation efforts, leading to a quicker recovery. In this analysis, GIS is used to assess and clearly portray the high, moderate, and low-risk areas for bioterrorism within certain parameters throughout San Diego County. The contributions of the resulting information include monitoring and surveillance as well as emergency preparedness, planning, and response. The specific parameters consist of aerosol dispersal of the biological agents, or pathogens, anthrax and plague with dissemination methods via devices such as airplanes, or ground detonation. This assessment comprises of locations of military bases or operations, population density, wind patterns, previous attacks, government buildings, public transportation, areas containing high profile people or projects, and areas in which the topography might influence the spread of the biological agent.

Chapter 1 Introduction

Though there are previously existing risk assessments for bioterrorism, inaccuracies or errors have been pointed out indicating room for improvement. On evaluating related work, the relevance of developing a successful model to aid in prevention and mitigation efforts is repeatedly stated. Thus, the research goal is to use GIS to improve upon the bioterrorism risk assessment methods, increase accuracy, and portray the information so that it is understood without much difficulty. The resulting information is relevant in understanding critical details in order to make appropriate decisions in the case of a bioterrorism attack. Although this analysis focuses on only two biological agents and one study area, the goal is that is can be utilized in any geographic location with any biological agents, or pathogens.

The spatial analysis performed considered two biological agents, anthrax and plague, as well as two dissemination methods of these agents. These methods consist of aerosol dispersal via aircraft or an explosive, ground detonated device that contains aerosols. For this analysis, GIS is used to indicate areas within San Diego County (figure 1) where a bioterrorist attack via aerosol dispersal is likely to occur, based on the environmental conditions, population, government building or operation locations, previous global targets, mass transit locations, and common large-scale event locations. The San Diego County area is particularly vulnerable to bioterrorist attacks due to the heavy concentration of military bases and personnel coupled with the high population density and event traffic. The performed research focuses on anthrax and plague dispersed by aircraft or explosion in determining areas of risk throughout the county.

1.1. Study Area

San Diego County is covers an area of 4,526 miles, according to the U.S. Census Bureau and has a population of about 3.2 million people. The county contains a variety of potential

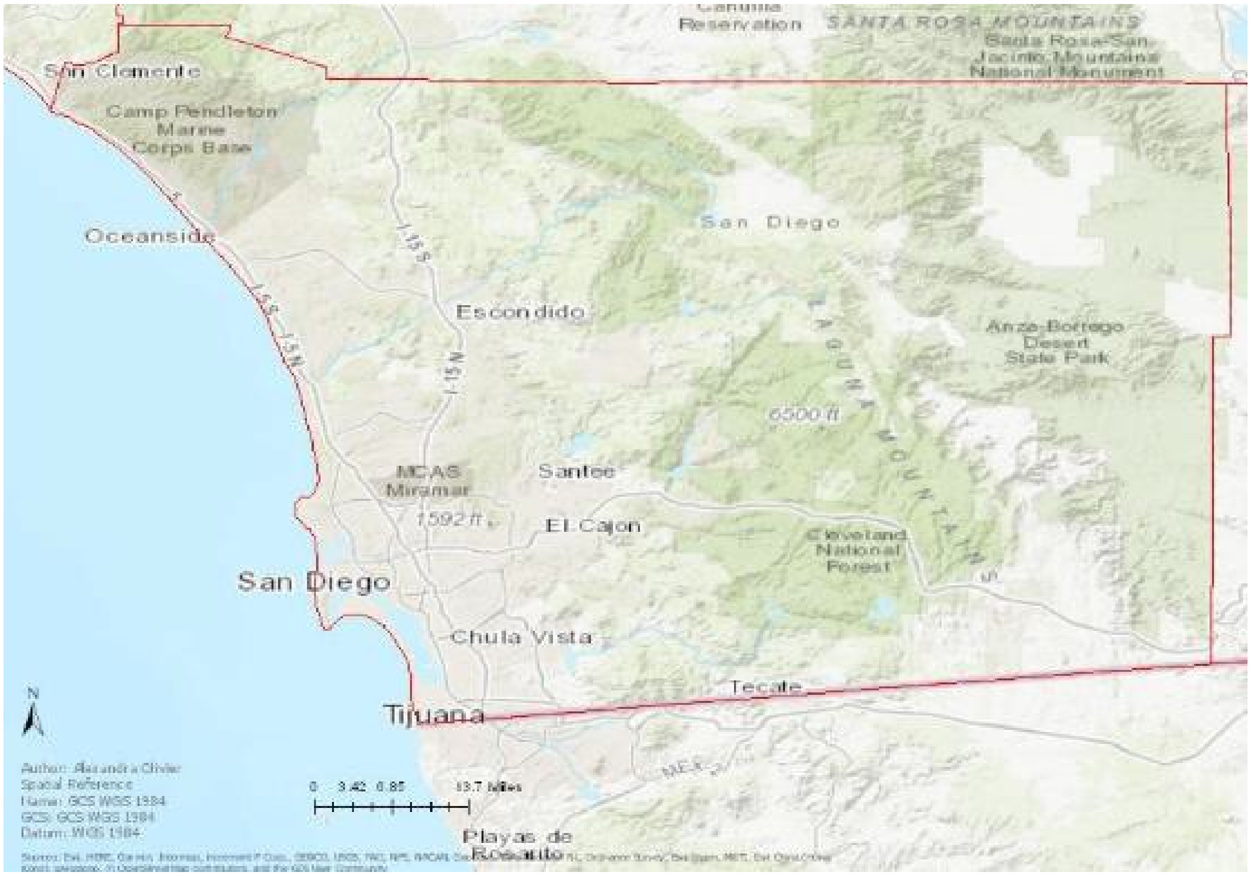

Figure 1. Outline indicating the research study area, San Diego County

contributing factors to a risk assessment for bioterrorism when analyzing previous attack data. This includes multiple military bases, military and defense companies, government buildings and officials, population density, transportation, and major attractions. Another potential contributing factor when observing the survivability and transmissibility of different pathogens is San Diego's varying climate and topography.

San Diego County has mountains, slopes, and peaks that can contribute to the acceleration of spread of a biological agent in the event of an attack. The climate and terrain of San Diego County contribute to the model in which the survivability of the pathogen within specific areas throughout the county is taken into consideration as well as the slope of the area of dispersal. There are 5 main climate zones within the county, which include the marine layer, transitional, inland, and desert. These diverse layers can support many different biological agents and can either increase or decrease the impact on the population dependent upon the environmental variables at the time of dispersal. The climate and terrain that the biological agent is dispersed in effects the impact that it has on the other variables. For example, there may be an increase in the area of contamination the steeper the slope, versus a more uniform contamination in flatter areas. The intensity of the impact to some level is dependent upon the survivability aspects of the biological agent and the slope of the area of dispersal. Being that the model considers climate as an important factor, this can present certain sensitivities and encourage the observance of microclimates.

1.2. Biological Agents and Dissemination Methods

The biological agents that this analysis focus on are considered Category A, high priority agents by the Center for Disease Control (CDC). These agents, or pathogens, were given this classification because they are easily spread and are capable of effectively impacting the population, posing a risk to national security (Robert et al. 2002). The dissemination methods of anthrax and plague can vary depending on factors like the particle size and environmental considerations. The methods being considered in this analysis are known as the traditional methods and consist of dispersal using spray devices or the incorporation with some explosive devices (Riedel 2004). The specific delivery devices taken into consideration for this analysis are aircrafts equipped with spray nozzles or systems capable of dispersing aerosols and ground detonated bomblets, or small bombs.

1.2.1. Anthrax

The reason that anthrax, or *Bacillus anthracis*, is likely to be used in bioterrorism is due to the extended survivability of the spores. Anthrax is capable of weaponization due to its ability of being released as an aerosol with minimal detection, as it cannot be sensed by sight, smell, or taste. It is transmissible via inhalation after being released into the air, which is more lethal than both contact or ingestion transmission. The survivability of the bacteria that causes anthrax is high, and it can last in the environment for years. It is most commonly found in agricultural regions of Central and South America, Asia, Europe, and the Caribbean (CDC 2015). Anthrax can survive harsh extreme temperatures, humidity, and ultraviolet light (CHS 2014). Although this robust pathogen is not prevalent to the United States there have been cases of anthrax by means of either biological attacks or sporadic outbreaks in animals such as cattle or deer. After inhalation, the infection can develop anywhere between one week to two months. Inhalation of anthrax is fatal and requires immediate, aggressive treatment for survival (CDC 2015).

1.2.2. Pneumonic Plague

Plague is caused by *Yersinia pestis* and is likely be used in bioterrorism due to its transmissibility and intensity. Plague affects humans and other mammals, typically after being bitten by or handling an animal carrying the pathogen. However, another reported form of transmission is via infectious aerosol droplets. A biological attack would affect both humans and animals, potentially increasing the outbreaks due to faster spreading by the animal carriers. Certain animals, including cats, can spread plague to humans via aerosols. This type of plague would be called pneumonic plague, which occurs when the disease is acquired by means of the respiratory tract. There is a delay of one to six days between being exposed and showing symptoms of the plague. This allows time for an exposed person to come in contact with many people during the gestation period, making it difficult to determine the source of the infection.

Survivability of the plague bacteria is not extensive in hot (over 80 degrees Fahrenheit), dry environments. Even so, airborne transmission can survive for up to one hour depending on conditions. Within this brief timespan, an exposed person (or animal) who inhales the released aerosols has an increased risk of becoming infected with the pneumonic plague. The size of the outbreak depends upon the quantity of biological agent released, the characteristics of the strain, and the environmental conditions at the time of release (Riedel 2005). It is possible for animals, such as cats, to infect people with pneumonic plague by the person inhaling the infectious droplets when close to the animal. To decrease high risk of death, antibiotics should be given within the first twenty-four hours of the first symptoms. In the situation of a bioterrorist attack this might be difficult given the delay between exposure and symptoms along with the amount of people exposed (CDC 2015). To gain perspective on the rate of infection, it has been reported that if 50 kg of plague bacteria were released in aerosolized form over a city of 5 million people then pneumonic plague could occur in as many as 150,000 persons, of which 36,000 expected to die. Still, the bacteria persist in the area for 1 hour at a distance of 10 km and people attempting to escape the area of infection further spreading the disease (Riedel 2005).

Most existing methods for bioterrorism risk assessment take different measures into consideration and focus on factors such as viral spread or the organization responsible for the bioterrorist attack and the perpetrator's behavior rather than vulnerable areas to an attack. Although similar methods include an approach taken by Misterek (2008), which is most like the approach taken in this study since it is a multifactorial risk analysis for a geographic region in the event of an airborne attack using anthrax. However, the main purpose differs in that it was to determine the most effective dissemination method of medicine regiments via emergency responders. Another study by MacIntyre et al (2006) also relates to the analysis in that it gives a relative risk ranking but differs because the risk ranking applies to all pathogens not considering the location or method of dispersal.

Other methods, such as the one by Pederson et al (2007) focus on using aerosol dispersion calculations to predict the area of contamination in the event of a bioterrorist attack via aerosols in relation to topography. Fellman et al (2011) as well as Parnell et al (2010) focused on the thoughts, behaviors, or decisions of the possible perpetrator(s). Another existing approach includes calculations for specific biological agents and the accompanying toxicity level in humans, a study done by Department of Homeland Security (DHS) 2008 and Fellman et al (2011).

The above-mentioned existing methods or models cover many approaches but scope for improvement remains. These existing methods lack different aspects, whether it be multiple variables environmental and demographic factors, or a combination of both. The literature on this topic is not vast, further validating the relevance of this thesis which fills gaps in existing methods as well as expand literature for future work.

1.3. Motivation

Bioterrorism has been identified by government agencies as an increasing threat in the United States that is predicted to continue increasing over time. According to documentation by the U.S. Government on assessing the threat of bioterrorism, the imminent reality of bioterrorism, the risk, threat assessment, and being prepared for these attacks has been discussed. This discussion was as recent as in the year 2014. It was stated that the risk of surprise is great and more preparedness, not less, is our greatest insurance policy for bioterrorist attacks. The risk in the United States is uncertain but a forthcoming reality and evaluating threat areas in addition to generating preparedness and response plans are critical prior to these attacks. These tasks require a credible and rapid means to detect and mitigate such attacks along with equally credible means to attribute and hold those accountable (U.S. Government 2014). All of these aspects are crucial for the impending impact on the United States.

In past situations, GIS has contributed to the emergency preparedness, planning, response, and recovery of different disastrous situations in numerous ways. The importance of this work is significant not only to aid with these efforts but is also relevant in educating or informing society on the topic in general. Providing visual representations that clearly portray the information is necessary for expanding individuals' knowledge on the topic. Gathering, compiling, analyzing, and distributing data efficiently is necessary in order to react appropriately to the situation. Areas such as San Diego already have an existing plan, but it needs to continuously be revised and improved upon when new information becomes available on contributing characteristics (Wells 2006).

San Diego has many contributing factors that make it a good candidate for a bioterrorist attack, such as a high density of military personnel and topography. According to Wolff and Asche (2015), city areas are considered more vulnerable than rural areas when it comes to man-made hazards like bioterrorism. This is due to the high concentration of technical, social, and traffic infrastructure in addition to their importance in politics, culture, economy, and finance. This research analysis allows for a successful assessment of potential threat areas for bioterrorism using anthrax or plague via aerosol dissemination across San Diego County and aid in preparedness, planning, and mitigation efforts.

This research would aid in the planning and preparedness for these attacks and the methods could be applied in other locations across the United States, being built upon or adjusted for improvements. The spatial analysis also contributes to the maintenance of effective disease surveillance and communication systems, which are fundamental components of an adequate public health infrastructure. Knowing potential threat areas for bioterrorism is beneficial in the development of a response plan, including preparedness phase, early warning phase, notification phase, response phase, and recovery phase (Beeching 2002). Having a response plan specific to the area can potentially decrease the number of deaths in the situation that an attack incurs which supports the importance of this research, while aiding in the mitigation efforts of the attack. Knowing areas that are more likely to suffer from a bioterrorism incident is valuable in many ways and contributes greatly to public health safety and homeland security (Kataoka 2007). The importance of this assessment continues to increase as society advances, and these types of attacks become more common.

The contributions of this research include but are not limited to, monitoring and surveillance for homeland security purposes, emergency preparedness and response plans, and aiding public health agencies. These contributions consist of various representations, such as modeling using ArcGIS, which provide relevant information for specific areas like public health surveillance (Lawson 2005). The results of the analysis are intended to indicate vulnerable areas to an aerosol bioterrorist attack in San Diego County using the designated biological agents and dissemination methods, with a risk level of high, moderate, or low. This information can be used to better secure and monitor areas with high population density, numerous government buildings or military bases, ideal environmental conditions, and are easily accessible. The results are intended to be utilized for assessment of the risk areas, the planning and mitigation of these events, as well as contribute to the ongoing analysis of bioterrorism patterns or potential threats throughout the nation (Grundmann 2014). The significance of this research increases over time as aerosol bioterrorism attacks become more widespread, as projected, given the continuous advances in science and technology. Following these advancements in science and technology is a potential increase for both modifications or mutations of biological agents as well as detection technology.

During World War II, bioterrorism became well known and utilized in various attacks which resulted in the start of an offensive biological warfare program in the United States. This program, started in the year 1942, was under the direction of the War Reserve Service which was a civilian agency. The offensive biological warfare program included a research and development center in Maryland located in what is known today as the US Army Medical Research Institute of Infectious Diseases. Along with this location, there were other testing facilities located in Utah and Mississippi as well as a production facility in Indiana (Riedel 2004). Bioterrorism preparedness planning, response, and mitigation became a better-known topic of discussion going forward.

The efforts put into bioterrorism testing and preparedness programs have been effective in the aspect that we are able to successfully test and prepare for such events. Included in this is the ability to train military personal in chemical and biological warfare. All preparedness, response, and mitigation planning is beneficial although it may not seem immediately effective to individuals in the event of an attack but more 'behind the scenes' mitigation and planning. National agencies who contribute to these efforts include the Center for Disease Control (CDC), the Department of Homeland Security (DHS), and the U.S. Department of Health and Human Services. Local agencies who contribute to preparedness planning documentation within the designated region, such as San Diego, include the County of San Diego, Public Health Services, and the Health and Human Services Agency.

Presently, San Diego County has a bioterrorism preparedness plan that indicates the specific programs that support or equip healthcare systems for these events along with locations of equipped healthcare facilities throughout the county. The latest revision of documentation found of this plan is from the year 2006, but it is unknown if an updated copy exists and is not publicly available. The local agencies responsible for managing and developing this plan include the Health and Human Services Agency, Public Health Services, and the County of San Diego. Additionally, the preparedness plan indicates the surveillance program, lab capabilities, alert networks, and communications in the event of an attack. The POD program, one of the programs in the plan, was assessed and rated among the best in the nation by the Center for Disease Control (CDC). Portable Dispensing Units (PODS) are empty containers commonly used for moving and storage across the nation. This program applied the first year to creating six portable PODS that are equipped as dispensing units for medications and instructions, which would be deployed to augment other distribution methods. The county continues to work on the mission of ensuring local readiness to minimize the impact on human lives from natural or man-made disaster (Wells 2006).

The results of this research would significantly contribute to the county's program by providing valuable information on high risk areas to an attack, allowing for revision of the equipment provided in the PODS in relation to the population density and disease type. Also, the resulting information would provide insight on the best locations to drop the equipped PODS in the event of an attack. The visual representation(s) indicating potential threat areas of bioterrorism via aerosol dissemination methods can be analyzed to determine the appropriate measures that should be taken to prepare for such an event. Additionally, the results provide a bioterrorism assessment model with visual representations to portray the information in a way that is easily understood and can be successfully disseminated to the appropriate agencies or organizations for the decision-making process in preparedness, prevention, and mitigation efforts.

1.4. Overview

The remaining chapters of this thesis cover details of existing models in related work, methodology applied, the results and discussion of the spatial analysis, and any challenges, lessons learned, and opportunities for future work. Chapter 2 covers details of the above-mentioned methods and models for a bioterrorism risk assessment. This includes scoring models, biological threat assessment, and a risk assessment for air-transmitted bioterrorism. The similarities and differences are compared to this thesis and the gaps in literature identified.

Chapter 3 covers the methodology of this thesis in detail, explaining which methods worked along with a brief explanation of the reasoning behind the application. This chapter provides clarification on the scoring system for the different variables and further explain the analysis process. The relevance of the individual data is described as well as the workflow processes with diagrams as appropriate.

Chapters 4 and 5 consist of the results of this thesis, the discussion, and the potential for future work. The visualizations included in these results clearly depict the information from the analysis so that it is somewhat straightforward, not requiring a complex process for comprehension of the result. If more than one method is applied for a specific section of the methodology, the results of each are discussed in chapter 4. Furthermore, the discussion contains not only the results and methods applied but also the challenges that presented themselves along with the lessons learned that contribute to the success of future work.

Chapter 2 Related Work

The articles discussed in this section indicate existing methods for performing a risk assessment for bioterrorism. The various approaches presented here include models specifically for air-transmitted bioterrorist attacks, the bioterrorism risk assessment scoring model, and the biological threat risk assessment (BTRA). Most of these models either focus on calculations specific to pathogens and environmental dispersal to determine spread, or behaviors of the potential attacker to assess risk. Whereas the thesis study presented here is a multifactorial analysis that considers variables such as environmental, demographics, and potential target locations. Although the discussed articles cover a variety of methods, there is a gap in literature closely related to a bioterrorism risk assessment model that focuses on the variables of a designated geographic location. The articles discussed provide sufficient information on the methodology, case studies, and concerns of these methods. The information obtained from the articles contributes to this thesis research, resulting in an improved risk assessment for air-transmitted bioterrorist attacks.

2.1. Risk Assessment for Air-Transmitted Bioterrorism

A case study in a professional writing by Misterek (2008) on emergency preparedness and planning using GIS focuses on a hypothetical bioterrorist attack involving the introduction of airborne anthrax to a metropolitan statistical area (MSA). Leading into the case study, the importance of GIS within emergency preparedness and planning is emphasized. The intentions of the study by Misterek (2008) are to explore the possibilities and challenges that accompany preparing a response plan using GIS at local government levels. The relevance of pre-planning is addressed and the critical role it has in effective deployment of crucial resources. The case study is presented to explore the strategies and variables used to prepare a response plan for a bioterrorism event in a designated area. While this is only one example of how GIS can be utilized in planning and preparation efforts for emergency response, it indicates the complexity involved and key criteria for the utilization of spatial analysis for response planning (Misterek 2008).

The case study in Misterek (2008) concentrates on how GIS might be utilized in designing a response via mail carrier to a bioterrorist attack, meaning that the postal service would deliver medical kits to the infected individuals. Although the case study focuses on anthrax, the article makes it a point to state that there are other bioterrorism possibilities, like botulism, plague, radiation, and smallpox. Any of these biological agents could have been utilized for a bioterrorist attack in a similar situation as anthrax.

The methods of this analysis include the collection of demographic and vector data for conversion to raster datasets, queries to parse values for the identified MSA, and data combined in ArcGIS and the Spatial Analyst extension. The criteria were determined based on availability and demographic factors explained in interviews with government officials who specialize in public safety and emergency preparedness. Combined data consisted of census tracts with the tabular sets of census data, using the join function, and each join was utilized to create a vector dataset. An example of a vector dataset used is one representing the number of individuals age 65+ and below poverty level. The datasets were classified into 10 classes using Jenks Natural Breaks then the vectors were converted to raster datasets with an output cell size of 200 meters. The raster conversion was performed using the Spatial Analyst extension. Then each of the datasets were reclassified, assigning a value to each class from 1 to 10 based on rate of occurrence for that census tract, 10 representing the highest vulnerability levels and 1 the lowest (Misterek 2008).

From here, each class was weighted by importance which was determined by how each category affects the ability of postal delivery to be effective. Assumptions were made when weighting the criteria as an example of how the technique might be applied. Weights were applied to each grid and the values combined using the raster calculator. The grids were combined for improved determination of the suitability of census tracts for targeted mail delivery of antibiotics. Finally, the tract polygons were converted into a point feature class which was then used in the spatial join with the zip code polygon feature for use in postal carrier assignments.

Upon final calculations, the results of the analysis indicated a calculated method that would best work in effective dissemination of medicine regimens by serving most of the populated areas of MSA. The main purpose of this analysis was to evaluate variables that may be considered to provide useful information to emergency responders in the event of an air-transmitted bioterrorist attack. The results of this spatial analysis aid in the decision-making process and contribute to future work (Misterek 2008).

The study presented by Misterek (2008) relates to this thesis in that it considers spatial location, similar methodology, and emphasizes the relevance of the information for emergency preparedness planning and response. Unlike other bioterrorism risk models, Misterek (2008) concentrates on demographic information within a geographic location rather than viral spread of the pathogen. Thus, this thesis differs from the study by Misterek (2008) in that it considers variables not only for medicine dispersal but a risk assessment for specific biological agents in a designated geographic region.

An additional study that takes location into consideration is by Pederson et al. (2007), where the criteria of focus are winds and topography. These criteria have proven to be beneficial in the prediction of contamination areas in a bioterrorism attack. The model presented in Pederson et al. (2007) combines these conditions with deposition velocity and degradation to generate a dispersion model which predicts an area of contamination for a biological agent dispersed in the form of aerosol. The results of this analysis include two models, one applying the dispersion calculation without the use of topography data and one applying the dispersion calculation incorporating topography data. In Figures 2 and 3, the effect of the variation in topography on the biological agent's dissemination in the situation of an attack is shown. Figure 2 shows the model that consists of the dispersion calculation without topography data, resulting in a uniform contaminated area. Figure 3 is the model that incorporates topography with the dispersion calculation for the biological agent, resulting in a slightly relocated, broader contamination area. Thus, the communities directly downhill or in a canyon might have an increased risk of a threat from air dispersal of a biological agent in an attack. The communities in these locations are also easily accessible due to the widening of distribution in space by wind and potentially topography (Pederson et al 2007).

The methods utilized in Pederson et al (2007) regarding aerosol dispersal of a biological agent were applied when a letter containing powdery material was opened in the postal facility. The police arrived at the facility and then contacted the bioterror response center to discuss the available information matching intelligence with threat characteristics. Soon afterwards, the situation called for dispersion calculations which involved those in Pederson et el (2007). Further analysis was performed using the models by Pederson et al (2007), indicating safe distances to research from the area of exposure, point of release, and wind dispersion models. In addition to the dispersion calculation, the resulting plume was analyzed using a geographical information system (GIS) to identify areas at risk. For instance, buildings with a high number of people such as schools and work places with many employees. Also included in the GIS analysis were institutions, especially those related to civil defense (medical labs, hospitals, government buildings, etc.). In conclusion, the various calculations and analysis performed provided information that would aid in the mitigation of a bioterrorist attack (Pederson et al 2007).

Although the study by Pederson et al. (2007) takes into consideration some of the same factors as the thesis study at hand, it differs in focus. Pederson et al. (2007) focus on calculating the spread of the biological agent upon aerosol dispersal whereas this thesis is a multifactorial analysis to result in a risk assessment for areas in a designated geographic region to a bioterrorist attack via aerosol of specified pathogens. While the analysis being performed does consider wind and topography as variables in relation to spread, the focus is not solely on calculations to predict areas of contamination.

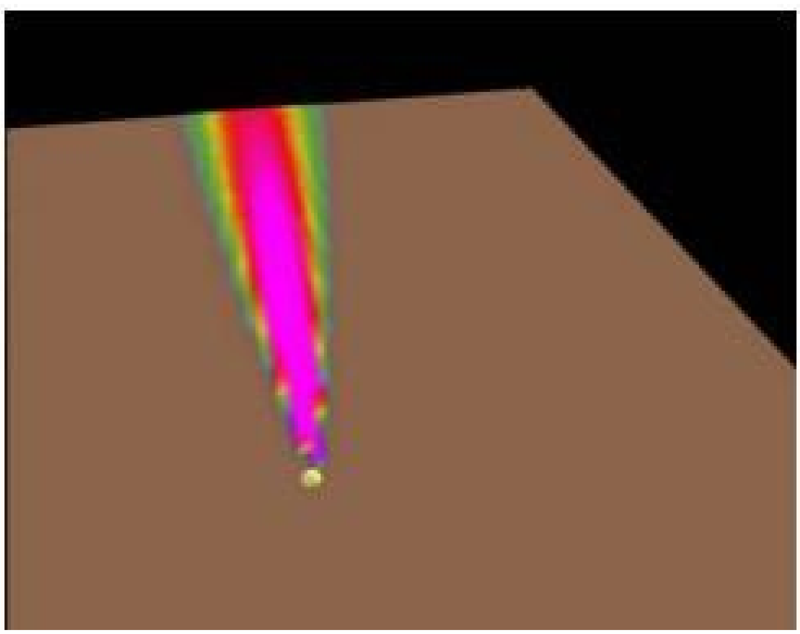

Figure 2. Dispersion calculation without use of topography data resulting in a uniform contaminated area (Pederson et al. 2007). (From Urban Dispersion Model by Defense Science and Technology Laboratory)

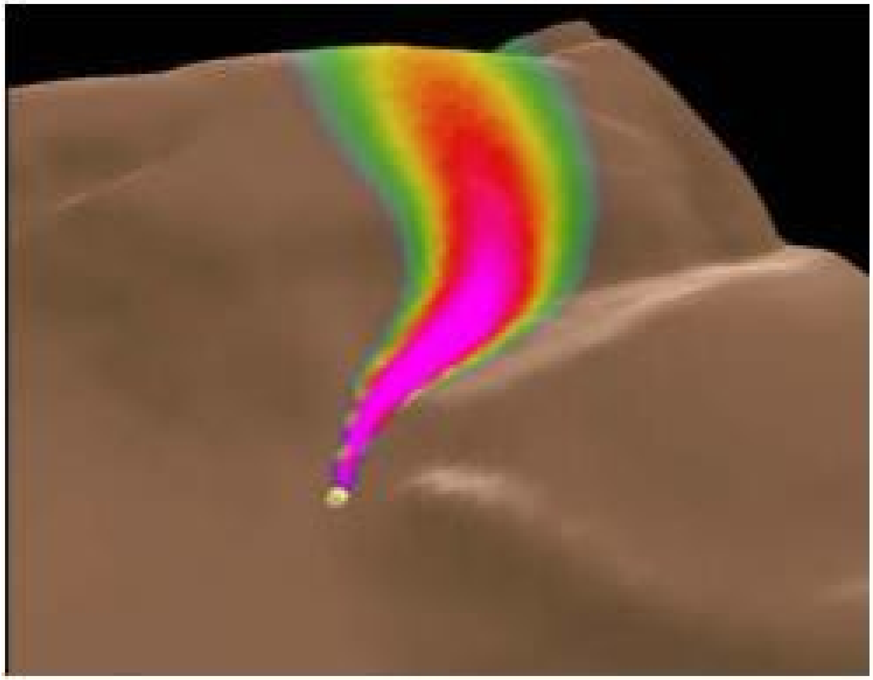

Figure 3. Dispersion calculation incorporating topography data, resulting in a somewhat relocated and broader contaminated area (Pederson et al. 2007). Dispersion calculation without use of topography data resulting in a uniform contaminated area. (From Urban Dispersion Model by Defense Science and Technology Laboratory)

2.2. Bioterrorism Risk Assessment Scoring Model

In the initial risk assessment performed by Radosavljevic et al. (2009), the focus was predetermining the groups responsible for the attacks rather than a vulnerability assessment. Issues or errors in the initial assessment were indicated when applied during the 2001 anthrax attacks and it was improved upon for more accurate results. The first assessment indicated a lack of data on the intent and ability of the perpetrators to perform an attack. A suggested solution was to utilize similar data but focus the model toward a vulnerability analysis. From here, a simpler model of bioterrorism risk assessment was proposed, applied, and compared to the previous model application in the 2001 anthrax attacks (Radosavljevic et al. 2009).

The scoring model discussed in Radosavljevic's study is an attempt to introduce a simple model of bioterrorism risk assessment scoring by classifying components, parameters, and types of bioterrorist attacks. This multi-step process first involves defining the targets that must be protected then the parameters for a biological attack, according to target(s). From here, an analysis must be performed of the most effective and simplest measures which would eliminate the defined parameters for an attack. The predefined parameters include perpetrator(s), agent, dispersion methods, and accessibility to both agent and target. Since it is difficult to predict the intentions of a potential attacker, the strategy applied was to limit vulnerability to prevent or mitigate biological attacks (Radosavljevic et al. 2009).

The purpose of Radosavljevic's model was to contribute to the understanding of vulnerability and potential consequences of an attack as well as the effectiveness of mitigation strategies. For comparison, the updated scoring model was applied the same way that the initial scoring model was in the 2001 anthrax attacks. The results indicated that the newer, simpler model is improved. In the specific process of the application, the agent, modified agent, letters sent from the U.S., targets, ability, secrecy, and repeated attacks were all taken into consideration. These factors were scored accordingly with a value of 0 or 1 indicating low or high probability under each suspect. The suspects in this example included terrorist, insider, and enemy state. The total score for the factors under each suspect was calculated and analyzed. The results indicated that the insider had the highest value of 10, terrorist the lowest value of 3, and enemy state in the middle with a value of 5.

The results of the initial model attempted to determine specific groups or organizations that may have planned the attack while the results of the updated analysis pointed to the most probable perpetrator being an insider. Radosavljevis et al. (2009) applied bioterrorist risk assessment methodology while considering variables like perpetrator behavior, targets, and biological agents, and accessibility. It is thought that this simpler bioterrorist risk assessment scoring model could be applied to shorten the time for mitigation of bioterrorist attacks and decrease risk in the event of an attack. It is also stated that the use of previous bioterrorist attacks might be beneficial in generating high-probability scenarios of attacks (Radosavljevic et al. 2009).

The study by Radosavljevic et al. (2009) first states an unsuccessful study then builds onto that study to propose an improved method, this is valuable information for anyone performing a similar study. The relevance of this information to this thesis is the contribution it can make to lessons learned, showing what did not work and suggested improvements. The study by Radosavljevic et al. (2009) also relates to this thesis by utilizing some of the same parameters, such as dispersion methods, agent, targets, and accessibility. The resulting information provides insight on the application of these variables in an analysis which contribute to improvements of this thesis. The two analyses differ on areas of emphasis, Radosavljevic concentrates on determining whom the perpetrator(s) were while the analysis in this thesis focuses on using multiple variables to determine low, moderate, and high-risk areas throughout a specific location.

A dissimilar scoring method used in MacIntyre et al. (2006), states that using the probability of an attack with a certain biological agent is the most common method of assigning priority. The goal of this study was to develop a multifactorial risk-priority system for category A bioterrorism agents. Category A biological agents are most likely to be used in an attack due to the severity and transmissibility of the infections, according to the Center for Disease Control (CDC). Unlike the previous study, the impact criteria included the stability of the agent in the environment as well as its potential impact on the population. Probability was assigned as the global availability, ease of weaponization, and historical examples of the agent for an attack. For each category A agent in these criteria, a score of 0 to 2 was assigned as: 0 for no, 1 for some/low, and 2 for yes/high. With a scale ranging from 0 to 20, the sum of the assigned scores indicate the rank priority. The results of this study indicate that anthrax is the highest-ranking priority of the category A biological agents. This study shows that a scoring system can be utilized to assign priority to biological agents (MacIntyre et al. 2006). Similar to this thesis, the study by MacIntyre et al. 2006 provides a relative risk ranking and considers specific biological pathogens. However, the risk ranking differs in MacIntyre et al. 2006 because it applies to pathogens no matter the location or dispersal method.

Though these methods differentiate in the criteria analyzed, they yield results that contribute to bioterrorism preparedness planning and mitigation. These studies are relevant to this thesis research because they utilize a scoring system to determine risk in bioterrorism. The application of these methods is sufficient for the end purpose, but there is room to expand upon these processes to improve the results. There appears to be a gap in literature for bioterrorism risk assessments that take into account the variations in dispersal location of the pathogen(s), in which this thesis research could contribute. The combination of these results with GIS are advantageous to the understanding of the situation as well as the efficiency of mitigation efforts. There are many useful tools that can be applied in performing a spatial analysis of this information (Kataoka 2007).

2.3. Biological Threat Risk Assessment (BTRA)

The Biological Threat Risk Assessment (BTRA) appears to be the most scrutinized for inaccuracies in literature and a proposed improvement to this model is the intelligent adversary risk model. Commonly used calculations for approaches such as the Bioterrorism Threat Risk Assessment (BTRA), rely heavily on the specific biological agent that may be used and its toxicity level in humans. This is a computer-based tool used to assess the relative likelihood and consequences of terrorists' employing each of the 28 pathogens indicated as potential terrorist threats by the CDC. The BTRA was designed to produce assessments in the form of risk-prioritized groups of biological agents. This assessment takes into consideration random variables representing terrorist decision making to determine the risk of intentional release of the biological agents. However, both Fellman et al. (2011) and the DHS (2008) have identified concerns of mathematical and statistical mistakes amongst other things in the BTRA model. These mistakes have led to potentially inaccurate results and overcomplicated models. It is for this reason that there are suggested improvements to the BTRA made by the National Research Council (NRC). One of the utilized suggestions is called the intelligent adversary risk model (Fellman et al. 2011).

The intelligent adversary risk model, rather than performing this risk assessment as if it were an uncertain hazard, models the behavior of an intelligent adversary or perpetrator(s). This risk model mainly takes human behavior into consideration, which can be difficult to account for or predict. It contains components related to the attacker's uncertain acquisition of the attack, target selection, method of attacks, the defender's risk mitigation actions, and uncertain consequences. This model is used in the decision-making process for decisions on the amount of vaccine for public health disease mitigation, adding cities to the monitoring program, and how to calculate the effects of a pathogen (Fellman et al 2011).

In this example, multiple objective decision analysis with risk is applied and it is assumed that the defender minimizes risk while the attacker increases risk. A decision tree is used rather than an event tree since potential attackers generally make the decision to achieve their objectives, ignoring the increased consequences they might inflict. Therefore, when using a decision tree, the attacker would choose the option that maximizes success, no matter the consequences. The decision tree model begins with decisions made by the defender to better prepare for the mitigation of bioterrorist attacks. It continues with deciding the amount of vaccine to store for the biological agent with the largest probability of being used and highest consequences. The more stored vaccine, the fewer consequences. The next step in the model is the attacker choosing an agent out of three possible choices in this model. Lastly, the probability of detection for each biological agent over time varies. Thus, more consequences to the population the longer it takes to detect. This model should be used with high quality, accurate data on the agents of concern. In conclusion, the results of the analysis demonstrate the likelihood of modeling intelligent adversary risk using decision analysis (Parnell et al. 2010).

The purpose of explaining the intelligent adversary risk model is to show the process for an existing method that was created as an improvement to the BTRA, in which errors were found by multiple agencies including the DHS. The aforementioned literature indicates a need for an improved bioterrorist risk assessment model that is capable of being applied in designated geographic locations for specific pathogens. The goal of this thesis is to study the existing methods, determine how they can be improved upon, determine contributing variables, and perform an analysis using GIS which results in a risk assessment model for air-transmitted bioterrorism that can be utilized at different locations. These results contribute to the lack of literature on this topic and provide valuable information for future work.

Chapter 3 Methods

The methodology for this spatial analysis involves the application of previously acquired knowledge and skills in GIS, analysis, and data science to sufficiently answer the research questions. The main question being, what are the low, moderate, and high-risk areas for a bioterrorist attack with anthrax or plague in San Diego County? Additionally, the results of the analysis answer how the risk areas vary given the infectious characteristics of the agent and by ground dispersal versus low-altitude aerial dispersal.

This analysis required some creation of original data, which was acquired via a combination of research methods and procedures from various websites, articles, and data warehouses. The data required to accomplish this research consisted of county data such as school and government building locations, population density derived from the U.S. Census along with the population table from the American Community Survey (ACS), analysis of facility types involved in previous attacks, topography, common large-scale event areas, wind patterns, military installations, government buildings, and public transportation. Along with this data, accessibility is taken into consideration as previously mentioned by analyzing features such as roads.

3.1. Variables Considered

There are numerous variables that were considered in the spatial analysis to contribute to a thorough, accurate assessment. These include aspects such as topography, wind classes for areas across San Diego County, mass transit locations (airports, train stations, etc.), locations of military bases, school locations, major attractions, locations of government buildings and other commonly known targets indicated by the data on previous global bioterrorist attacks. After the collection and organization of this information, an assessment was performed to rank risk for a bioterrorist attack using anthrax or plague and the specified dispersal methods throughout San Diego County. This analysis entailed the use of tools such as search by attribute, various queries, weighted overlay, IsNull, Con, and clipping within GIS. From here, maps were generated using ArcGIS, which indicate the potential threat areas, ranging from areas of high risk, moderate risk, and low risk.

The data on previous attacks throughout the world was analyzed to determine any potential patterns related to target areas. This information indicates targets that were successfully attacked and are be applied to the analysis, resulting in an increase in the weight assigned to the layers containing these previously targeted areas. The dataset for previous targets was generated from researching and acquiring publicly available information on historical attacks. The sources of this data include professional publications on historical or previous attacks, the RAND Database of Worldwide Terrorist Incidents (RDWTI), the Global Terrorism Database (GTD), and reliable news sources for attacks more recent than 2016. After collection the data was analyzed to determine the most and least commonly attacked targets in biological and chemical attacks. Percentages were calculated upon analysis of this information to use as the weights of each layer in weighted overlay. Chemical attacks were also included in the analysis to improve accuracy in the risk assessment model due to the similarities in dispersal methods and target areas.

The method of deriving values for a risk scale is be comparable to prior research, while also taking into consideration the previously targeted areas. For example, if a government building is indicated as a common target within the previous global bioterrorist attack data then areas containing government buildings throughout the county have an increased risk. Finally, using the above-mentioned variables with their assigned risk values and weights, a spatial analysis is performed to determine the level of risk of the area to an attack.

Observing and analyzing topographic data of the area provides insight into potential areas where it may be relatively simple to achieve an attack via air dispersal as well as areas where the topography might increase the spread perimeter of the biological agent dispersed in the attack. As previously mentioned, topography has been used in the prediction of areas of contamination in a bioterrorism attack (Pederson et al. 2007). In the study by Pederson et al. 2007, this information combined with deposition velocity, degradation, and weather has been applied to generate a dispersion model that predicts an area of contamination. The resulting information is beneficial to preparedness planning and mitigation by indicating areas that may be impacted more by the dissemination of the biological agent. An area with little to no obstacles, such as an open field, is easily accessible, though the contamination area might not be as broad in a very flat area due to the reasons discussed previously. Areas with complex topography may make dissemination more difficult and discourage an attack on the area, or it may completely impede the dispersal of an aerosol within a sufficient range for an effective attack via aircraft.

Another valuable consideration is accessibility, which can indicate the weak points of security for the area, increasing the probability for harmful activity or attack. For example, if the area is easily accessible and not secure it is more likely that an individual could succeed in an attack if desired, with dissemination methods appropriate to the situation such as a helicopter, drone, or ground detonated biological weapon. The measure of accessibility is derived from the results of an analysis of specific data like road access, airspace, and transit routes. For example, an analysis of data signifying roads and where they lead are considered as well as fly and no-fly zones, where it is potentially more difficult to successfully complete an attack undetected. This information in combination with the location of government buildings, military bases, major attractions, schools, wind, and densely populated areas can indicate locations that might be at higher risk of an attack due to the potential impact on the population. The aforementioned data is gathered, and a spatial analysis performed using GIS to calculate the areas with high, moderate, and low risk for a bioterrorism attack via aerosol with the indicated biological agents and dispersal methods within San Diego County.

3.2. Methodology

The methodology of this analysis involved data collection, analysis, database creation, preparation of data for use in the weighted overlay tool, generation of process in ArcGIS Pro ModelBuilder, and generation of visual representations. The process is most similar to the related work by Misterek (2008) but differs in additional datasets and calculations. Due to a lack of available literature with the desired methodology using previous attacks there were estimations

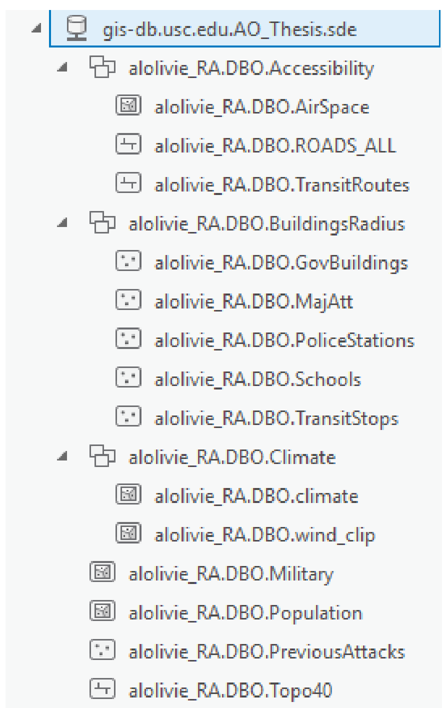

Figure 4. SQL server database where the data is housed, enabled as an enterprise geodatabase.

and assumptions made with close consideration and analysis of the previous attack data. These steps are indicated with asterisks in figure 7. All required datasets were obtained from reliable sources and generated where necessary prior to being organized within the SQL database (Figure 1). It is crucial to obtain data from reliable sources to sustain credibility and produce accurate results. The SQL database was enabled as an enterprise geodatabase using the geoprocessing tool, allowing for the data to be stored in SQL Server Management Studio while capable of being utilized in the ArcGIS spatial analysis. This database is also the output location of the final product of the models created in ModelBuilder. The geodatabase created within ArcGIS Pro was the output location for the model process. The last step, weighted overlay, is put into the SQL database rather than the ArcGIS Pro geodatabase because this is the resulting raster which shows the results of the spatial analysis. Having a specific location and method on housing the data potentially reduces human error and aid in the prevention of inaccuracies in the analysis.

3.2.1. Data Preparation

The various datasets required steps for preparation to be utilized in the weighted overlay tool, such as queries, feature to raster, assigning values to the NoData cells, and reclassification. Depending on the type and size of dataset, this process may differ. All datasets are in the same coordinate system, NAD83 StatePlane California VI FIPS 0406 Feet, to ensure that the measurements correspond. The datasets were analyzed to confirm the correct formatting, which includes normalization and lack of abnormalities within the data. Additionally, examination of the collected datasets ensured all information had been gathered for a successful assessment, including historical data and data that contributes to measurement of accessibility. This consists of known target areas or conditions that have been indicated from global historic data on attacks, including road access to locations like military operations or government buildings.

For files such as military operations, it was necessary to select only the locations of these operations or bases within San Diego County. In this case, the select tool was used to select only the San Diego County locations then exporting the selected features to a new feature class. The wind dataset from the National Renewable Energy Laboratory (NREL) shows the wind power density classes throughout areas of San Diego County (Table 1). Wind power density, although typically used to evaluate available wind resource, tells us the wind speed that correlates with the class. The factors used in the calculation to determine wind power density are beneficial in this risk assessment, such as wind speed.

Table 1. Classes of Wind Power Density at 164 feet

Wind Power Class	Speed (mph)
1	0-12.5
2	12.6-14.3
3	14.4-15.7
4	15.8-16.8
5	16.9-17.9
6	18.0-19.7
7	> 19.7

A demographic dataset from the products by the U.S. Census Bureau was joined with an age and sex table from the American Community Survey (ACS) in order to calculate population density. The first step of this calculation was to calculate the total area in square kilometers by adding the land and water fields together, which are in meters, then dividing by one million. A new field for density was created and calculated by dividing the area in square kilometers by the total population of the specific area, indicated in the American Community Survey data. Since the projection of the datasets are in U.S. feet, a new field was created in the attribute table to convert density to people per square mile rather than square kilometer. To calculate this field, the density in square kilometers was divided by .62 square miles being that one square kilometer is equal to .62 square miles.

The datasets containing building locations are point files which may not adequately account for these locations in the risk assessment model. For a better representation of these datasets in the assessment, a multiple ring buffer was generated with values between 0 and 1,500 feet. In Maurer 2009, it was conveyed that Britain's first bioweapons were to deliver anthrax to a target via aerosols emitted by bomb detonation. The radius of the bomb impact was reportedly up to 1,500 feet away from the detonation site. Also, the Department of Homeland Security states that the radius of an improvised explosive device (IED) ranges from 0 to 1,570 feet depending on the size of the bomb. The evacuation distance for a bomb the size of a semi-trailer is 1,570 feet. Since this is the evacuation distance and the tests mentioned in Mauer 2009 specifically use anthrax bombs, and there is not a buffer measured in the previous literature, a buffer of 1,500 feet is used for all point files. This buffer, used to account for every building location, is an estimated radius of an attack in which the purpose is to harm the personnel inside and surrounding the building.

Additionally, to measure accessibility in the ground detonation model, a near table was generated on the roads data and transit routes to determine the distance from each point location to the nearest roads or routes. These datasets containing the distances to the closest feature were used in the analysis, the smaller values being higher risk and the larger distances the lower. The distances from every road and transit route to the closest features were used to measure accessibility. The closer distances to the roads or transit routes being the higher risk zones, the farther the lower values the lower risk zones. Airspace is considered in the accessibility analysis for aircraft dispersion in the place of roads and transit routes. Obtaining knowledge of fly zones contributes to measuring accessibility. Aircrafts might be more suspect in an area outside of a fly zone rather than in a fly zone, increasing the risk within the fly zone. In the reclassification step, these features were classified by size, the large the size of an area the higher the risk of an attack.

From here, conversion of the datasets was performed using the feature class to raster conversion tool within ArcGIS. The parameters of the conversions were an output cell size of 656 feet, equivalent to the 200 meters shown in prior related work. In preparation to be used in the weighted overlay tool, the isNull and Con (conditional) tools in ArcGIS were used on the layers that are smaller than the extent of San Diego County. These included all building location layers as well as roads, military, and transportation locations. Since the layers did not cover the same extent, when run through weighted overlay NoData values were filled into the areas where the layers did not overlap. The IsNull tool assigns a value of 0 to these cells that would contain NoData. The conditional tool then states that if a cell has a value of one, assign a value of zero and if the cell does not have a value of one, assign the value from the original file. This results in the NoData cells having a value of zero while the other cells keep their original value from the raster file, allowing the dataset to be successfully utilized in the weighted overlay tool.

To accomplish a successful assessment, an applicable method to determine risk values within the classes, along with percentage weights are assessed to determine risk levels. Being that this calculation was not in the previous literature, the methodology was determined for the weighted percentages upon close analysis of the data. Climate information was not available for the previous attack data which posed difficulty, resulting in estimated percentages for the weighted overlay using the determined methodology and calculations. Reclassification is performed on all raster datasets, leading to the scoring values from 1 to 10 which indicate risk of a bioterrorist attack using anthrax or plague and the designated dispersal methods across San Diego County.

Similar to the methods in existing research models, the risk threshold values were generated via reclassification of the dataset into 10 classes based on the specific field used for feature to raster conversion, such as population density, size, or location in relation to an area. For example, smaller military operations are lower risk while larger military operations are higher risk. Exceptions to the 10 classes include the wind layer and the climate layer. The wind layer includes 7 wind classes as indicated by methods used in calculating wind power density. The climate indicates the 5 main climate zones of San Diego County, coastal, interior, transitional, desert, and maritime zones. To account for fewer classes as well as importance, the assigned weighted value for these layers is multiplied by the specified value based on importance and increased by 2.

3.2.2. Weighted Overlay Variables

For the final part of the spatial analysis, a weighted overlay is performed with all raster datasets using the weighted overlay tool in ArcGIS. Each raster dataset is assigned a weighted percentage determined by a former analysis of previous attack data to indicate the potential risk factor of specific targets analyzed in the assessment. The various layers were weighed by their importance in the risk assessment model and the impact the conditions might have on the area in the situation of an aerosol attack.

In the right environmental conditions, an aerosol attack of a biological agent can have a huge impact on the population. Wind speed is critical to the risk assessment as it affects the number of people impacted by the attack, thus the weighted percentage is increased based on the importance. This increased risk factor is supported by Maurer 2009, where it is stated that winds below 5 mph are too slow to efficiently carry the pathogen but winds above 30 mph degrade the pathogen. The wind power classes shown in table 1 are well within these values. Slope across the county was calculated from 40-foot topography data and considered in the analysis. To do so, the topo to raster tool was used on the contour lines dataset then the slope tool was used to calculate the slope values across the county in feet. As seen formerly in the model by Pederson et. al. as well as mentioned in Maurer 2009, wind and topography play important roles in the effectiveness of a biological attack via aerosols. Due to the importance in these variables determining the impact on the remainder of the considered variables, both wind and slope have increased percentages for weighted overlay.

Climate is crucial to the survivability of each pathogen and the impact it makes on the population. As previously mentioned, anthrax spores can survive extreme environmental conditions. It is for this reason that the climate layer in the anthrax model is reclassified to one class with a value of 1, representing equal risk in all climate zones of San Diego County. Pneumonic plague does not survive for an extensive amount of time in low humidity and high temperatures, therefore the desert climate zone is a lower risk than the coastal areas of San Diego County. For the model containing the pneumonic plague, the climate remains in the 5 classes indicating which areas are high and low risk based on the survivability of pneumonic plague. The pneumonic plague model uses the same weighed value for consistency across the models.

The building locations taken into account for this analysis are indicated as targets in the historical data and are considered to be prospective targets in the event of an attack. The above-mentioned buffers were used in the analysis to account for each building location, the closer range being the higher risk. The relevance of these locations as well as the surrounding area in the analysis is reinforced by Maurer 2009, where the distinction is made between outdoor and indoor decay rates. The pathogens decay quicker outdoors due to environmental conditions, including UV light, while indoors increases the lifespan of the pathogen. This information corresponds with the closer distance being high risk and farther distance lower risk areas.

The assigned percentages for the weighted overlay are based on the previous target data as well as the probable effect of the variable on the area in the case of an anthrax or plague attack via aerosols on the population and economy. These percentages must add up to 100% total and are not equally weighed. It is almost certain that equal weights would not result in an accurate assessment since, in reality, the variables are not considered equally. The percentage values were determined by first dividing the number of attacks on a specific target by the total attacks from the early 1900s to the year 2017, rounding to the nearest integer, and multiplying by 100 to get the percentage. There were 380 total recorded biological and chemical attacks, which are shown in Table 2.

Since accessibility and climate were not covered in the previous target data a methodology was developed after analysis of the data to account for these additional categories. As mentioned previously, the climate data is not available in the previous attack data thus a method was estimated based on the available information. First, 3% was subtracted from the percentage value of each target to account for the added categories. The targets within the 'other' category is not considered in the analysis, thus the percentage (13%) of 'other' in addition to the 21% just subtracted from the other categories make up the climate and accessibility percentages. The total percentage to split between these categories being 34%. The categories or variables that this percentage is split between vary with the model, whether aircraft or ground detonation dispersion model.

Table 2. Number of attacks on previous targets on a global scale from the early 1900s to 2017.

Category	Number of attacks	Percent of attacks	Description of target
Major Attractions	31	8%	Businesses
Population	73	19%	Citizens, tourists
School	46	12%	Educational Institutions
Government	81	21%	Diplomatic/general government buildings, political parties, national government officials
Military	38	10%	Military operations
Police	40	11%	Police stations/operation centers
Transportation	23	6%	Aircraft/airports, other transportation
Other	48	13%	Maritime, journalists/media, food, water, unknown, utilities, terrorists, cult or religious affiliations
Total	380	100%	

In running the weighted overlay tool, the various raster datasets are overlain in ArcGIS where the numerical values are multiplied by the percentage then added together for a single raster output. The resulting values of the weighted overlay indicate the levels of risk, the lowest value indicating the lower risk areas, the highest value the higher risk areas while the median of the values indicates areas of moderate risk. This process is used to evaluate the potential risk of a bioterrorism attack via aerosol dispersal of anthrax or plague to the areas within San Diego County, rating them from areas of high risk, moderate risk, and low risk as determined by the designated numerical values. This model is run a total of four times, once for each pathogen and for each dispersion method. From here, visual representations were generated indicating the areas and their associated risk levels for bioterrorist attacks using anthrax or plague dispersed via aircraft or ground detonation via aerosol throughout San Diego County. The risk levels are represented by three colors indicating the level of severity (red=high, orange=medium, yellow=low). Areas with complex structure or difficult visibility are increased in size, creating an inset map of the desired areas.

3.2.2. Aerosol dispersion of biological agents via aircraft

First, the original ‘other’ percentage of 13% is divided to the nearest integer between wind, slope, climate, and airspace, resulting in 3% for each category. Since survivability of the biological agent depends on climate, it is more important than wind, slope, and airspace in relation to the potential impact on the other variables. The initial percentage of 3% is multiplied by 4 to account for increased importance, totaling a weight of 12%. Since this class was one that was reclassified to fewer than 10 classes, a value of 2 is added to the percentage to compensate, resulting in 14%.

Wind speed along with slope impact the effects of the biological agent on other variables, such as population and building locations. As mentioned before, environmental variables have a significant effect on the impact of the attack and whether it remains slowly traveling within a flat open area or at an accelerated rate with the right wind speeds and topography. With that being said, the percentage value for wind is multiplied by 3 based on the importance regarding the potential impact on the other variables such as population or building/operation locations. Additionally, a value of two was added to the resulting percentage since this dataset reclassified to less than 10 classes in order to keep the original preset wind classes of 1 to 7. The final weight for wind being 11%.

In addition to wind, slope may increase the acceleration of a biological agent, increasing the risk for the aforementioned variables in the affected area. Thus, the slope value was multiplied by 2 for a resulting weight of 6%. This leaves a remainder of 3% for airspace, which indicates fly zones for each commercial or military airport in the extent of the county. Including this data contributes to the assessment by providing access points for an aircraft to potentially fly undetected for a substantial amount of time. While flying outside of fly zones would be a lower risk of a successful attack due to being outside of regulations, causing immediate suspicion. An overview of the process and final weighted percentages are shown in Table 3.

Table 3. The weighted overlay percentages used in the aircraft dispersion model.

Datasets and weighted percentages for the dispersion of biological agent via aircraft				
Datasets	**Original Percentage minus 3**	**Factor of increase (multiply)**	**Additional added value (add)**	**Weighed Percentage for overlay**
Major attractions	5%			5%
Police stations	8%			8%
Population Density	16%			16%
Military	7%			7%
School	9%			9%
Government	18%			18%
Transportation	3%			3%
Airspace	3%			3%
Slope	3%	2		6%
Wind	3%	3	+2	11%
Climate	3%	4	+2	14%
TOTAL				100%

The risk assessment model for aircraft dispersion is run twice, once for anthrax and once for pneumonic plague, with the same percentages. While the percentages remain the same between the pathogens, the variation lies within the classification of the climate dataset. As mentioned before the climate dataset was reclassified based on the survivability of the pathogens in the environment. The climate dataset for anthrax for reclassified to indicate equal risk across the county since *Bacillus anthracis,* is a resistant pathogen and can survive hot, humid, dry, and extreme temperatures. While *Yersinia pestis,* the bacteria that causes plague, thrives in less dry areas with temperatures typically below 80 degrees Fahrenheit. Therefore, the climate dataset is kept in the original 5 zones but reclassified to indicate the increased risk areas due to survivability of pneumonic plague.

The model for aerosol dispersion of biological agents via aircraft dispersal is shown in Figure 5. This model is made up of various geoprocessing tools, generating output files for both anthrax and plague. The model for this process mentioned above was generated using ModelBuilder in ArcGIS. The beginning data, the data that goes into the weighted overlay, and the results are indicated as parameters by a 'P' in the upper right corner. The parameters were set so that they may be changed easily when the model is utilized in the future and when running via the geoprocessing window. When running via the geoprocessing window, the datasets indicated as parameters are visible in the window and are added to the map after the model is run. All datasets that required a 1500-foot buffer be made are grouped together inside the yellow box seen in Figure 5. This was done to provide clarity and organization to the model. Since the same dispersion method is being used for both pathogens, the same weighted variables are applied. However, reclassification of the climate dataset differentiates for the pneumonic plague in that the risk varies dependent upon the climate zone in relation to the survivability of the pathogen. After the model was run successfully, the symbology of the outputs was classified using Jenks Natural Break Method to display three colors representing low, moderate, and high risk. Red represents high risk, orange represents moderate risk, and yellow represents low risk areas throughout the county.

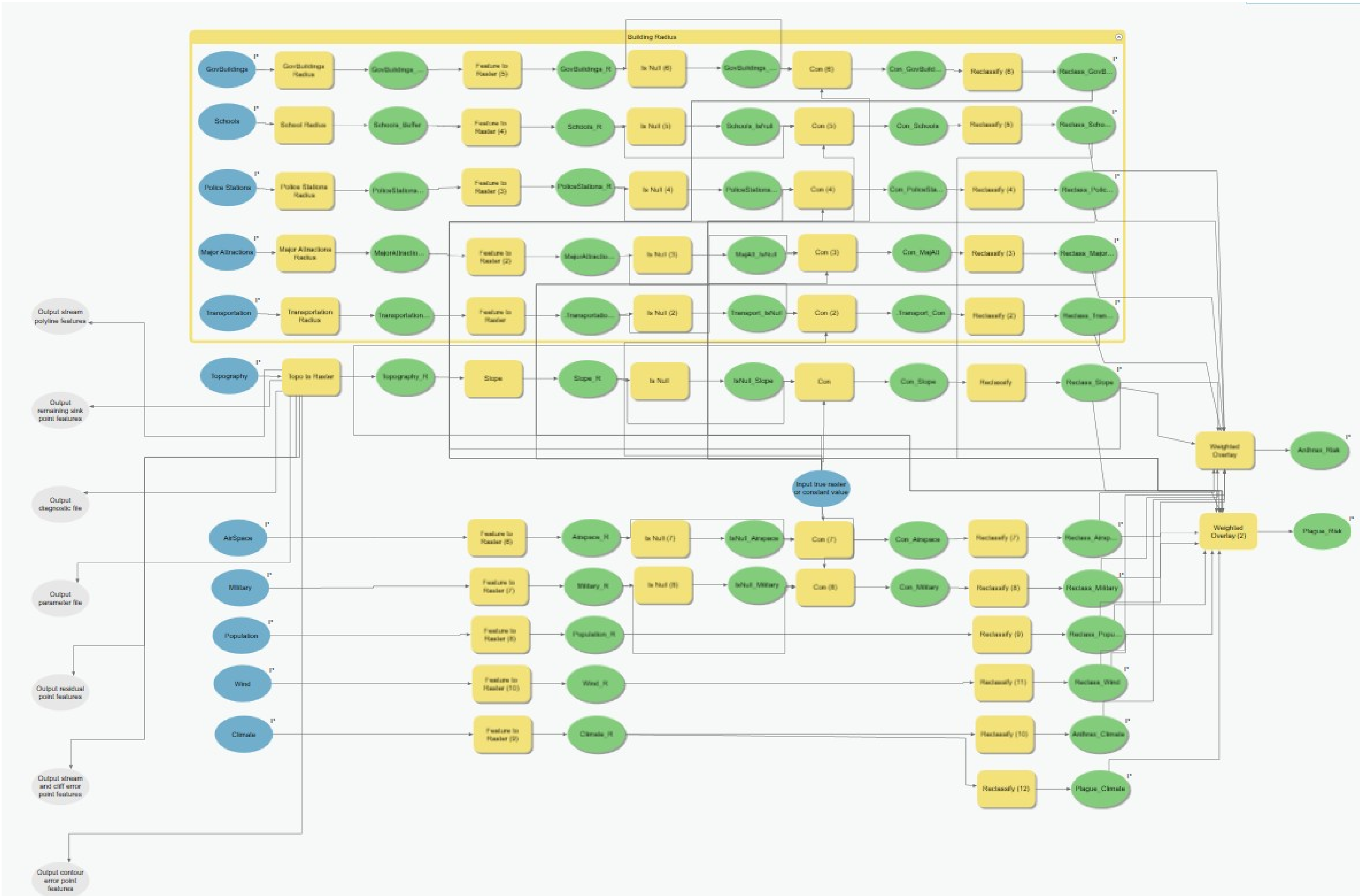

Figure 5. Risk assessment model for aircraft dispersion method, outputting risk assessments for both anthrax and plague.

3.2.4. Aerosol dispersion of biological agents via ground detonation

There are minor differences between the model using aircraft dispersal and the one using ground detonation. These models differentiate in the variables used to measure accessibility and their associated weights. To account for accessibility in the aircraft model, airspace was observed, while in the ground detonation model this is replaced with datasets containing roads and transit routes. A near analysis table is generated using each of these variable datasets for both the roads and transit routes datasets, indicating the distance in feet of the roads and transit routes to each variable. For example, the near analysis is performed using government buildings and schools to indicate the distance of the roads and transit routes to each of these. This distance is utilized in the analysis, the closer distances signifying higher risk and the farther, lower risk. After the near table is generated, a join is performed for the roads near table to the roads layer and a join between the transit routes near table and layer. From here, the datasets are exported into new files, run through the 'IsNull' and conditional tool, then reclassified. Then these reclassified layers are able to be used in the weighted overlay.

The weighted percentages differ in the accessibility variables for this model. The roads layer remains the same weight as the airspace layer in the aircraft model and the transit routes layer is also 3%. Although slope is still a relevant factor in this analysis, due to the angle of dispersion in the aircraft model slope had a more significant effect on the impact of the biological agent than in the ground detonation model. It is for this reason that the slope percentage is decreased by 3% and this 3% is distributed to the other accessibility factor, transit routes. The weighted percentages for the ground detonation model are shown in Table 4.

Table 4. The weighted overlay percentages used in the ground detonation dispersion model.

Datasets and weighted percentages for biological agent dispersal via ground detonation				
Dataset	**Original Percentage minus 3**	**Factor of increase (multiply)**	**Factor of increase (add)**	**Weighed Percentage for overlay**
Major attractions	5%			5%
Police stations	8%			8%
Population Density	16%			16%
Military	7%			7%
School	9%			9%
Government	18%			18%
Transportation	3%			3%
Roads	3%			3%
Transit Routes	3%			3%
Slope	3%			3%
Wind	3%	3	+2	11%
Climate	3%	4	+2	14%
TOTAL				100%

Using ModelBuilder in ArcGIS, a risk assessment model for ground detonation dispersal method of biological agents via aerosol was generated (Figure 6). This model is comparable to the model for the aircraft dispersal method in that it has many similar considered variables, as is shown above in Table 4. As previously mentioned, the models differentiate in accessibility factors. Aircraft dissemination of aerosols observes airspace while dissemination via ground detonation observes roads and transit routes. This information is valuable in determining what is more easily accessible without potentially seeming suspicious. The model for ground detonation dispersal method also outputs two files, one for anthrax and one for pneumonic plague. Like the aircraft dispersal method, these two pathogens differentiate in how the climate dataset is reclassified dependent upon ideal environments for survivability. Although, this reclassification remains the same as the model using the aircraft dispersal method.

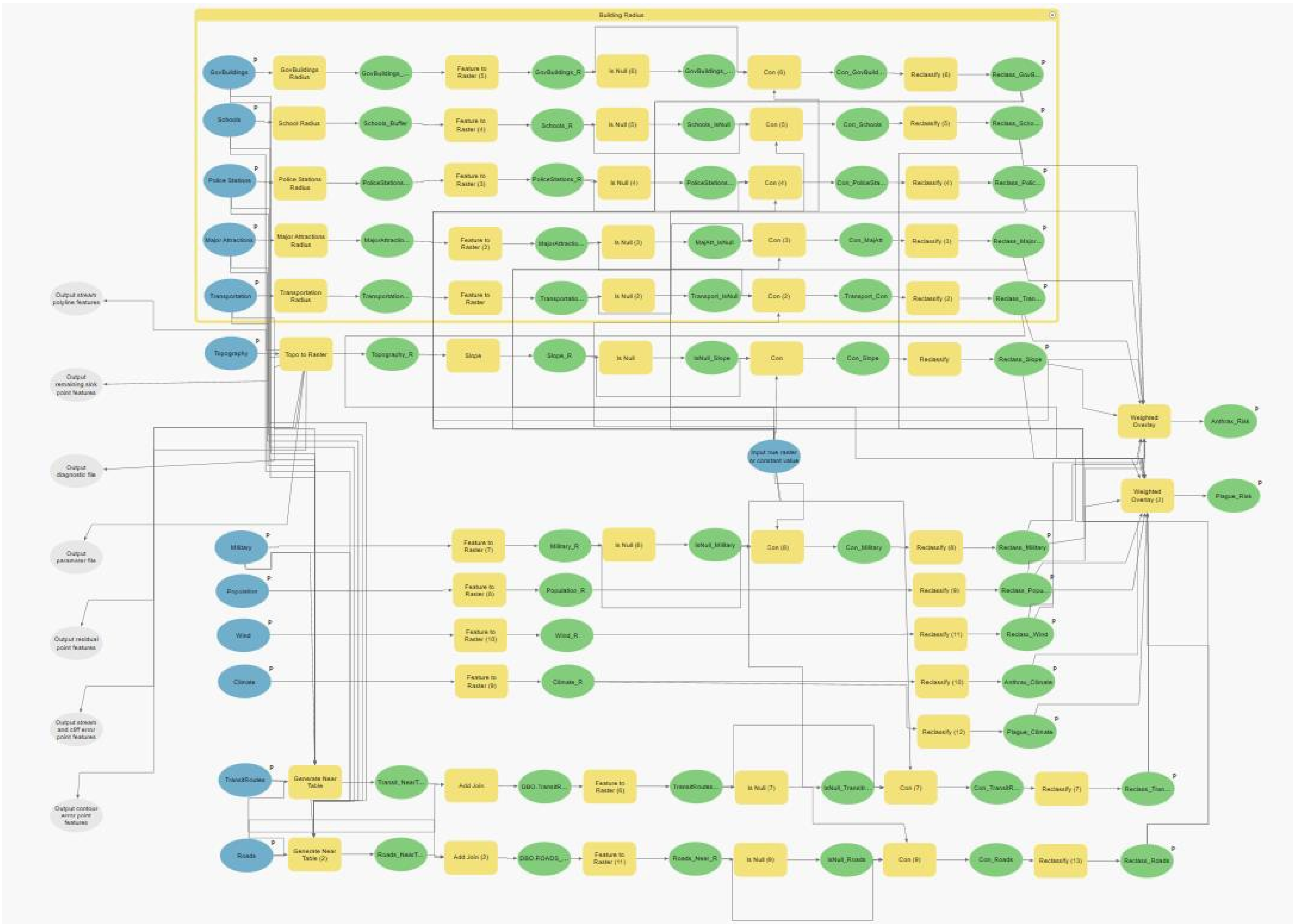

Figure 6. Risk assessment model for ground dispersion method, outputting risk assessments for both anthrax and plague.

The information in Table 5 indicates the necessary datasets to successfully complete the spatial analysis.

Table 5. Required datasets for the analysis.

Data	Source	Format	Availability	Temporal Scale	Purpose
2010 Census Data	U.S. Census Bureau	shapefile	open source	2010 Census	Demographic information such as population, which is used to calculate population density.
Wind	National Renewable Energy Laboratory (NREL)	shapefile	open source	November 2011	Nationwide wind data to analyze in combination with topography to assess the risk level of the spread of a biological agent in the case of an attack.
Military Installations/Operations	Data.gov	shapefile	open source	October 2008	Information regarding the locations of military operations which are a variable in the risk assessment.
Previous attacks/targets	Global Terrorism Database, RAND Database of Worldwide Terrorist Incidents, reliable news reports, published papers on historical attacks	shapefile (s)	This dataset was developed using the following procedure: 1. Gathering & cleaning of data into an excel document 2. Import excel file into ArcGIS. 3. Display locations by X/Y coordinates of attacks. 4. Export to shapefile.	1915 to 2017	Provides historical information on successful attacks, target areas, and agents used. This indicates most common target areas which are considered in the analysis of San Diego County. Potential target data considered within the county matches the known targets in this information (schools, government buildings, etc.).
Schools	County of San Diego	shapefile	open source	October 2017	Schools are indicated as a target area in the historical data and contribute to the risk analysis.
Government buildings	County of San Diego	CSV	open source	Updated April 2015	Provides information on the location of government buildings and key personnel whom work in these buildings, which are a

					variable in the risk assessment.
Mass transit routes & stations	SanGIS	Shapefile (s)	open source	Updated June-July 2018	Provides information on the transportation, or movement, of people as well as main transit points which are variables in the risk assessment. This includes airport locations.
Airspace	SanGIS	shapefile	open source	January 2010	Provides information on the fly zones and restricted fly zones throughout San Diego County to contribute to the measurement of accessibility and the analysis of aerosol dispersion.
Topography	SanGIS	shapefile	open source	September 2009	Provides terrain data which is analyzed against the wind data to determine the potential spread of a biological agent in the event of an attack.
Survivability & transmissibility of biological agents	Center for Disease Control (CDC), credible journal articles	PDFs	open source	N/A	The information gathered from the sources on survivability, transmissibility, and ideal conditions for the biological agents are taken into consideration against other variables in the analysis.
Roads	SanGIS	shapefile	open source	Updated August 2018	This information is used to better measure accessibility.
Climate	SanGIS	shapefile	open source	Updated April 2015	This information contributes to risk of each biological agent in an area based on ideal climates for the pathogen(s) survival.
Major attractions	SanGIS	shapefile	open source	April 2015	Provides information on the locations of major attractions which may indicate areas of increased risk across the county.

3.4. Research Design

The research design or workflow that was followed for this analysis is shown in Figure 7.

Figure 7. Overview of the spatial analysis process.

Chapter 4 Results and Discussion

The datasets were overlain, their accompanying weights multiplied by the assigned value (1 through 10) and added together to generate a raster product indicative of low, moderate, and high-risk areas throughout the county. The results of this analysis consist of four visualizations, one for each pathogen for both aircraft and ground detonation dissemination methods. The variation between the risk assessments for each pathogen are noticeable in the resulting visualizations. Due to the differences in survivability within certain climates and accessibility, respiratory anthrax appears to be a higher risk to San Diego County than the pneumonic plague via aircraft dissemination method.

4.1. Risk assessment for aerosol attacks via aircraft dispersion method

The effectiveness of an aerosol attack via aircraft distribution method depends on several factors but varies significantly from biological agent to biological agent. The impact on an area relies on certain properties of the biological agent, or pathogen, in relation to the area. For instance, the survivability of the pathogen in the climate of the study area plays an important role in the effectiveness of the pathogen as well as wind speeds which can determine the spread of the pathogen. The aerosol dispersal of anthrax could lead to numerous cases of respiratory anthrax in humans, which is stated to be the most dangerous type of anthrax in comparison to cutaneous (skin) or gastrointestinal. The aerosol dispersal of plague could lead to numerous cases of pneumonic plague in both animals and humans, which is also deemed the most fatal type of plague. The transmission of pneumonic plague differs in that it can be spread not only human to human but animal to human. However, the ideal climate for plague is more limited than anthrax, thriving in more humid locations with warm temperatures during the day but cooler at night.

4.1.1. Anthrax aerosol attacks via aircraft dispersion method

Noticeable in the visualizations, there is an increased risk for respiratory anthrax via aircraft dispersal in comparison to pneumonic plague. The results shown in figure 8 represent areas of low, moderate, and high risk across San Diego County for an aerosol dispersal of anthrax. Much of the county is represented as orange, which is moderate risk, while few areas are yellow or low risk, and the areas that are red specify areas of high risk. A significant portion of the county is represented as moderate risk, which is most likely due to the fact that the bacteria which causes anthrax is able to thrive in most environments for a significant amount of time. The low risk areas in this model, though there are few, are near the outer edge of the designated radius for building locations while the high-risk areas are located in the mountains, highly concentrated areas, and a large military base.

The few low risk areas in the county are focused near downtown and central San Diego where there is a high concentration of population, government buildings, major attractions, police stations, and schools. The inset map in figure 8 zooms in on a cluster of building locations, confirming that the low risk areas are the outer edge of the 1,500-foot building radius. Though small, it is noticeable that the inner radius of the building locations is either moderate or high risk in comparison to the outer edge. The building location was utilized in the assessment as a potential target with a 1,500-foot buffer, as indicated by previous military testing on aerosol bomb impact, explaining the reasoning why the actual building location is the highest risk. Even though the buffers are consistent, the risk varies contingent upon the weight applied during the weighted overlay. For instance, government buildings have a higher weight in the overlay therefore an increased risk is displayed in the resulting visualization.

The moderate risk areas, represented in figure 8 as orange, cover most of the county for the anthrax aerosol dispersion via aircraft model. The most probable reasoning for this is that anthrax can withstand various environmental conditions, causing increased risk across the county no matter the climate. As stated in the methodology section, the climate for anthrax was of equal risk throughout the county and strongly weighted due to its importance in the impact of the pathogen. When the weighted overlay occurred, the layers that most impacted this increased risk across the county are wind, climate, population, and government buildings in combination with the remaining layers.

The high-risk areas shown in figure 8 consist of a large military base, locations with generally higher winds, ideal climate, and the radius of certain building locations. The wind class for the high-risk areas that are more inland range from 5 to 7 on the scale shown in table 1, which include wind speeds of 16.9 mph and higher. These increased wind speeds in combination with the slope may accelerate the spread of a released pathogen in this area, resulting in a higher risk value. The desert and some mountainous areas are where high-risk is indicated more inland. These areas have increased wind speeds which may increase the spread of a biological agent and the impact it has on the population. The larger high-risk polygon in the top left corner of the county is a large, highly populated military base. The fact that this area is densely populated and is a large military base mainly contributes to the level of risk. The smaller red, high risk areas spread throughout the coastal region of the map are the building locations. These areas are indicative of the higher risk zones of the various 1,500-foot buffers created previously.

Using both the zonal statistics and geometry tools, a summary table was compiled which displays the total coverage area of each risk level and population information such as average population per square mile within the designated risk zone (table 6). From observing this table, it is noticeable that the moderate risk area covers most (91.3%) of the county while the low risk area covers the least (0.8%) and high risk covering only 7.9% of the county area. In relation to population, the risk levels do not coincide with population density throughout the area. It is believed that this result is due to the sensitivity of the model to climate data, which might be improved by revisiting the climate variables utilized in the model. In the low risk areas, the average population density per square mile is about 3,464 people per square mile, while it is 424 people per square mile in the moderate risk areas, and 743 people per square mile in the high-risk areas. When comparing these results to the visualization, the correlation with the areas that each risk level covers was confirmed. Overall, the moderate zone covers the largest area of San Diego County and includes about 81.5% of the total population. An attack in high-risk areas could potentially put 12.3% of the population at risk and an attack in a low risk area could impact about 6.2% of the population dependent upon the area of attack. It is probable that an attack on a high-risk area would significantly impact the population and surroundings due to the location of these zones. Due to the scope of the moderate area, it is improbable that a bioterrorist attack within this area would affect roughly 81% of the population but rather the population within a subset of the area.

Table 6. Resulting statistics of the anthrax aircraft model.

Anthrax Aircraft Model				
Risk Level	Area (square miles)	Percent Coverage	Average population per square mile	Percent of total population
Low	35.79650138	0.8%	3,464	6.2%
Moderate	3865.932048	91.3%	424	81.5%
High	334.0698163	7.9%	743	12.3%

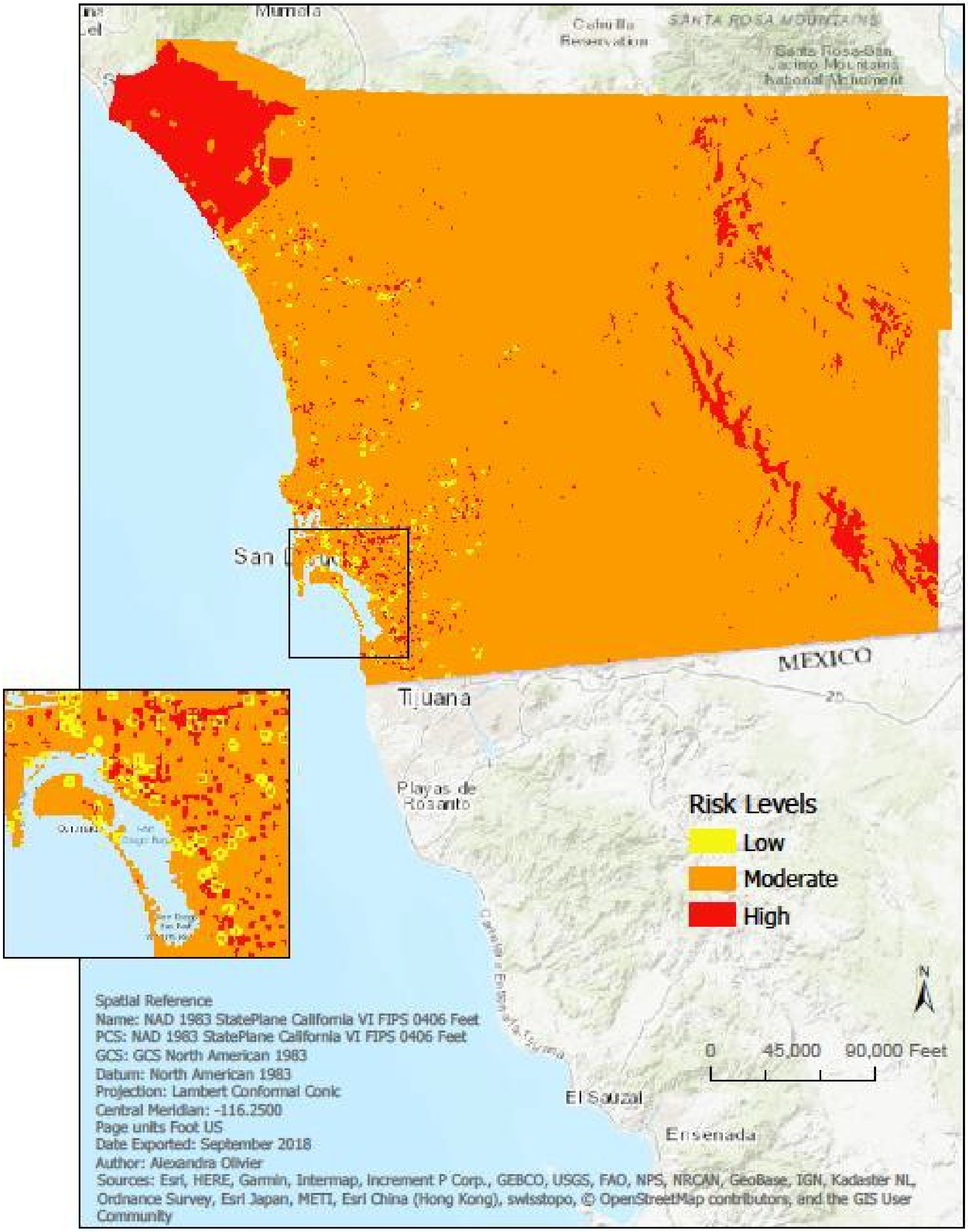

Figure 8. Risk assessment for aerosol dispersal of anthrax via aircraft.

4.1.2. Plague aerosol attacks via aircraft dispersion method

The results of the risk assessment for plague across San Diego County reflect the previously presented information on the ideal climates where this pathogen may survive. Overall, the risk areas for the aircraft dispersal of plague across the county is significantly less than the dispersal of anthrax. As shown in figure 9, there are minimal high-risk areas and more low and moderate risk areas. Since this pathogen only thrives in certain climates, much of the county is low risk. The climate dataset had a significant impact on the results due to the weight of the dataset being higher because of its importance.

Looking back at the ideal climate information for the pathogen confirms the reasoning for the moderate risk area running down the coast of the county. The mix of low to moderate risk areas more inland represent mountainous and desert areas. The mountainous areas have moderate winds and terrain with steeper slopes, resulting in an increased risk in this analysis. The desert areas typically fall within wind classes between 5 and 7, which is 16.9 mph and greater. The mountainous areas typically fall between 3 and 5, which is 14.4 to 17.9 mph. The terrain in both areas could contribute to accelerated spreading of the pathogen. Thus, the topography dataset which was used to calculate slope contributed to increased risk in the resulting visualization. The other dataset with an increased weighted value is the wind dataset, which also contributed to the moderate risk areas in the desert and mountainous climate zones of San Diego County.

The high-risk areas for plague are mostly along the coastline, which coincides with the above-mentioned results. The major contributing factors to the high-risk areas in the resulting visualization are most likely from the climate, population, and radius of building locations. In comparison to figure 8, plague does not pose as high a risk as anthrax, but this is because anthrax can survive extreme environmental conditions. Consequently, capable of having a substantial effect on the population.

The zonal statistics and geometry were analyzed to determine the results in table 7 which show that the low risk level covers 72.4% of the county, the moderate risk level 26.9%, and high risk only 0.7%. The average population per square mile within each risk zone is indicated, the low risk areas being the lowest with an average of about 340 people per square mile, the moderate risk 680, and the high-risk areas the highest 6,727 people per square mile. Unlike the previous result from the anthrax via aircraft model, the results from this analysis more closely relate to population density. Apart from the moderate risk zone towards the mountains and desert areas more inland, the resulting high and moderate risk areas are more densely populated than the low risk areas. The zone that covers most of San Diego County is low risk and contains approximately 61.8% of the population. The moderate risk area contains roughly 36.1% of the population, while in comparison high-risk areas include only 2.1%. It is highly probable that an attack in the moderate risk area along the coast would impact a substantial portion of the population included in this area. This is due to the population density along the coast being significantly higher than the density more inland.

Table 7. Resulting statistics of the plague aircraft model.

Plague Aircraft Model				
Risk Level	Area (square miles)	Percent Coverage	Average population per square mile	Percent of total population
Low	3065.563563	72.4%	340	61.8%
Moderate	1141.30483	26.9%	680	36.1%
High	2894283747	0.7%	6,727	2.1%

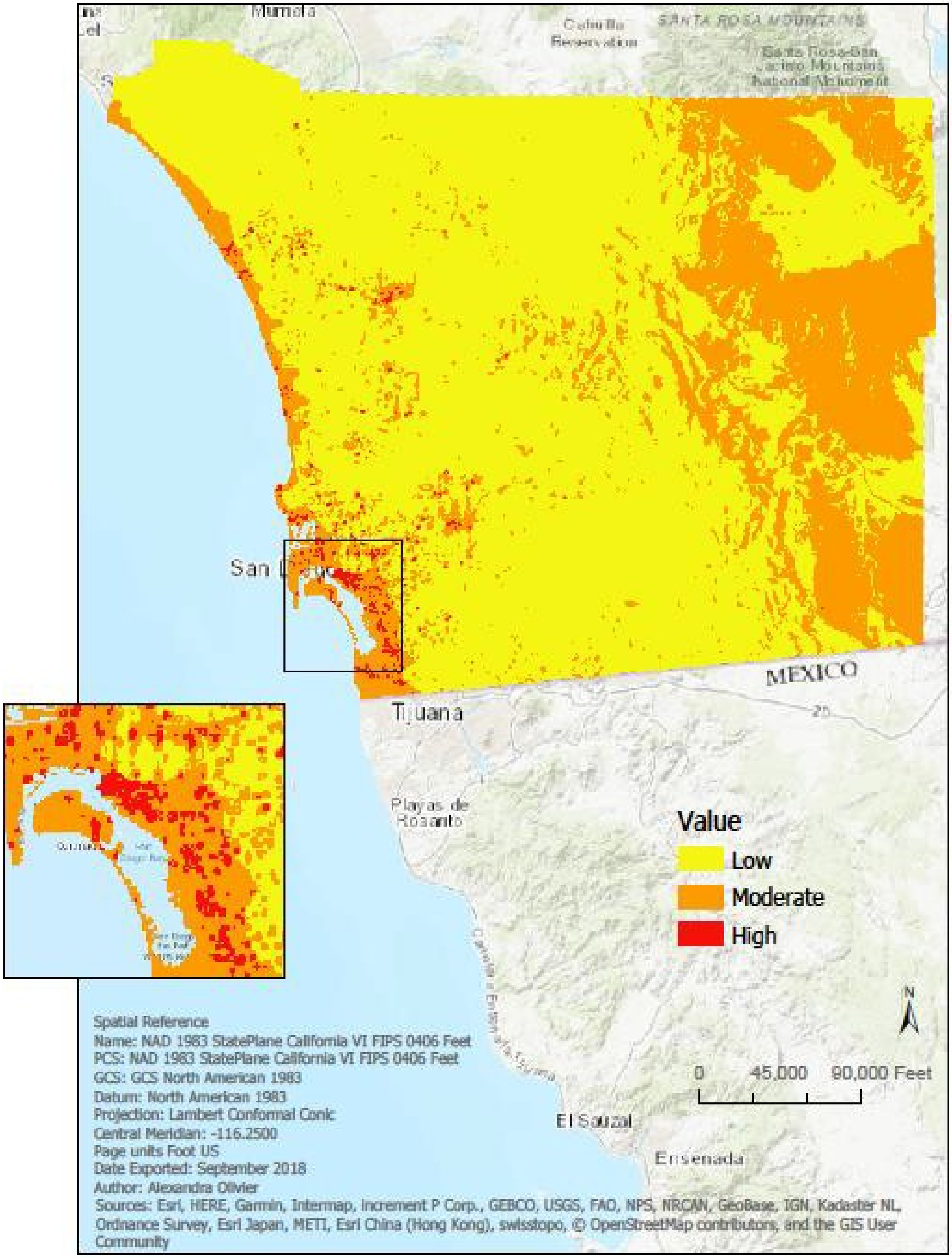

Figure 9. Risk assessment for aerosol dispersal of plague via aircraft.

4.2. Risk assessment for aerosol attacks via ground detonation dispersal

The adjustments made to the aircraft model to become a ground model seem minor but have a substantial impact on the resulting visualization. The main adjustment being the datasets used to measure accessibility, transit routes and roads. The distances from these datasets to the nearest building location or military base were used in this risk assessment to contribute to the accessibility measurement. The ground detonation dissemination method appears to have an increased risk for anthrax but a decreased risk for plague in comparison to the aircraft dissemination method.

4.2.1. Anthrax aerosol attacks via ground detonation dispersal

Figure 10 represents the results of the analysis for anthrax aerosol attacks via ground detonation dispersal method. In comparison to the aircraft dispersal method, this visualization indicates an increase in high-risk areas. The reasoning for this variation is that the airspace dataset was removed, the slope weight was decreased by 3% and the roads and transit routes datasets were added. This is feasible due to the impact of the release of a pathogen at ground level versus released in the air at a specific altitude. Releasing into the air allows more area for the pathogen to diffuse across in the time it takes to reach the surface where it impacts the population. Of course, many other factors such as wind and climate contribute to this as well. As previously mentioned, environmental conditions greatly influence the success of a biological attack. Releasing a pathogen at ground level provides more of a confined space which could lead to greater impact on the surrounding population.

The areas of low risk consist of building locations with a lower weighted value, such as transportation or major attractions. The moderate risk areas consist of more densely populated areas that have many roads, increasing accessibility to the various locations indicated by the datasets. Since anthrax is capable of surviving in most climates, in combination all of the other variables such as high population density, roads, transportation routes, and transit stops, there are not many low risk areas throughout the county.

The moderate areas are where there are a high number of roads, transportation, population density, and building locations that were identified as potential targets. Also, in the moderate risk areas there are higher winds and potentially ideal climate zones. The vast differences in the resulting visualizations between the aircraft method and the ground detonation method are due to the removal of airspace regions near airports and the addition of the roads and transit routes near distances layer. The near distance reclassification consisted of the lower values which were closer to the roads being the higher risk and the farther the distance to the roads, the lower risk. The roads dataset utilized was for all reported roads throughout the county, whether paved or not. This immense dataset was used rather than only major roads to increase accuracy in the measurement of accessibility. There is a substantial rise in the high-risk areas in comparison to the results of the aircraft model. This is due to the use of data containing all roads in San Diego County as well as transit routes in this analysis. Areas that are indicated as high risk include high population density, winds, ideal climate, and potential target areas with increased weighted values.

The statistics shown in table 8 specify the coverage of each low, moderate, and high-risk area in relation to San Diego County and the population. Even though the moderate and high-risk areas are nearly equal, the high-risk area covers the majority of San Diego County, 52%. The moderate risk area covers 47.5% and the low risk area covers 0.6% of San Diego County. These results emphasize the increase in high-risk between the aircraft and ground model, further indicating the room for improvements to the model. Improving the model could consist of revisiting the environmental variables and potentially adding spatial and temporal climate data. Since climate data such as wind speeds and temperatures were not available for the previous attack data, the model requires more manipulation across different aspects to improve accuracy. As observed in the anthrax via aircraft dispersal model, the risk level does not correlate with population. The low risk area has an average population of 3,202 per square mile, moderate risk 513 per square mile, and high risk 411 per square mile. The risk level should relate in some ways to the population as seen in the results containing plague. The main difference between the two pathogens is the survivability of anthrax versus plague, which is why it is suspected that more detailed environmental variables would improve the results for biological agents like anthrax. The high-risk area, though covering most of the county, only includes about 45.0% of the population while the moderate area covers about 51.3% of the population. When analyzing the visualization, it is noticeable that a portion of the high-risk area is more inland in a not so densely populated area. The low risk area only includes about 3.7% of the total population. In this situation, an attack on either the moderate or high-risk areas would impact a subset of the specified population within the zones due to their extent. The coastal areas, including downtown San Diego, are where an attack would be more effective due to the population density, concentration of important government buildings, military bases, and major attractions or events.

Table 8. Resulting statistics of the anthrax ground model.

Anthrax Ground Model				
Risk Level	Area (square miles)	Percent Coverage	Average population per square mile	Percent of total population
Low	23.43212121	0.6%	3,202	3.7%
Moderate	2009.944977	47.5%	513	51.3%
High	2202.434215	52.0%	411	45.0%

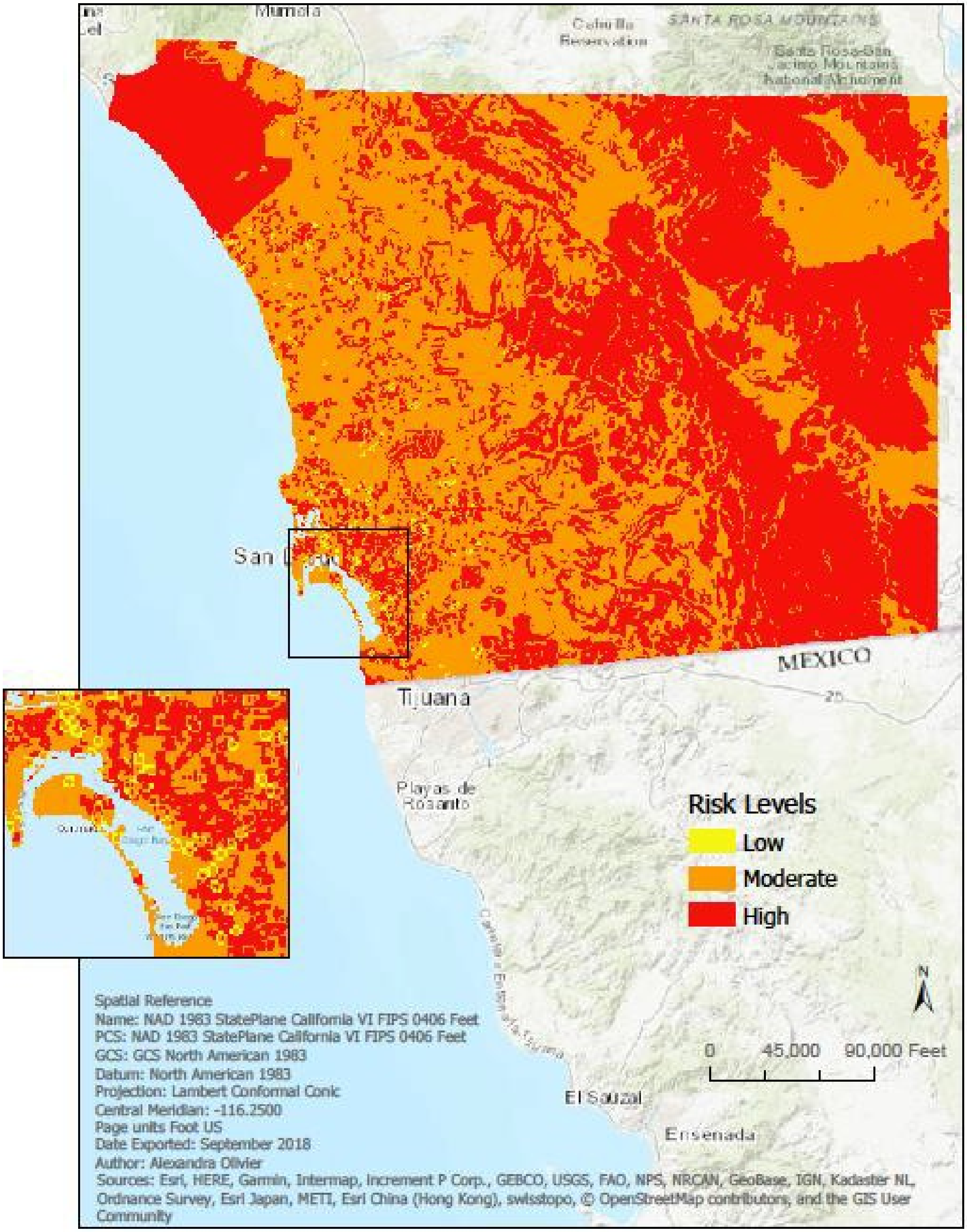

Figure 10. Risk assessment for aerosol dispersal of anthrax via ground detonation.

4.2.2. Plague aerosol attacks via ground detonation dispersal

There was also variation between the results for aircraft dispersal of plague and ground detonation. There is an overall lower risk when it comes to dissemination via ground detonation of an aerosol form of plague. Much of the county is low risk with a few areas of moderate and high risk spread throughout. As previously mentioned, the adjustment in datasets decreased the weight of slope and removed airspace, in turn lessening the moderate risk values inland towards the desert and mountainous areas.

The low risk areas across the county might be an indicator that a successful attack via plague would be contingent upon the environmental conditions. Unlike anthrax, where the conditions may influence the impact, but the pathogen is likely to persist in most climates. The accessibility data appears to have offset some of the factors causing many areas to be moderate risk. The increase in low risk towards the mountainous and desert regions could be due to the decrease in slope and increase in roads and transit routes. The transit routes and roads distance to the closest feature was used to determine risk within the area. This may have caused a decrease in moderate risk, even in the highly populated area shown within the inset map in figure 11.

The moderate risk areas are mostly within higher wind zones, which have been mentioned to have wind classes between 5 and 7, and also within densely populated areas with a large concentration of government buildings. The high-risk areas are mainly in downtown and central San Diego which are areas of dense population, major attractions, events, and other building locations.

The statistical results in table 9 indicate the largest area of coverage as the low risk area, covering 95.8% of the county, and containing around 75.95% of the population with a population density of 376 people per square mile. These results, much like the result from the aircraft model, can be related to population density of the county. The moderate risk area contains about

20.47% of the population but the average population density is 2,461 people per square mile. The high-risk area includes only 3.58% of the population, with an average density of 7,296 people per square mile. Between the aircraft and ground model, the moderate risk area has decreased while the low risk area has increased. This could be the result of either decreasing the importance of slope, removing the airspace model, or adding the roads and transit route datasets. Most of the high and moderate risk areas are in the zoomed in portion of the map, which is the central San Diego area. This area consists of high population density, concentration of key buildings, transit stops, major attractions, and military bases. The success of an attack on this area is highly probable and would likely impact a significant portion of the population in this area, even more so when taking into consideration the transmissibility and gestation period of the bacteria that causes plague.

Table 9. Resulting statistics of the plague ground model.

Plague Ground Model				
Risk Level	Area (square miles)	Percent Coverage	Average population per square mile	Percent of total population
Low	4058.44955	95.8%	376	75.95%
Moderate	167.4979982	4.0%	2,461	20.47%
High	9.863719008	0.2%	7,296	3.58%

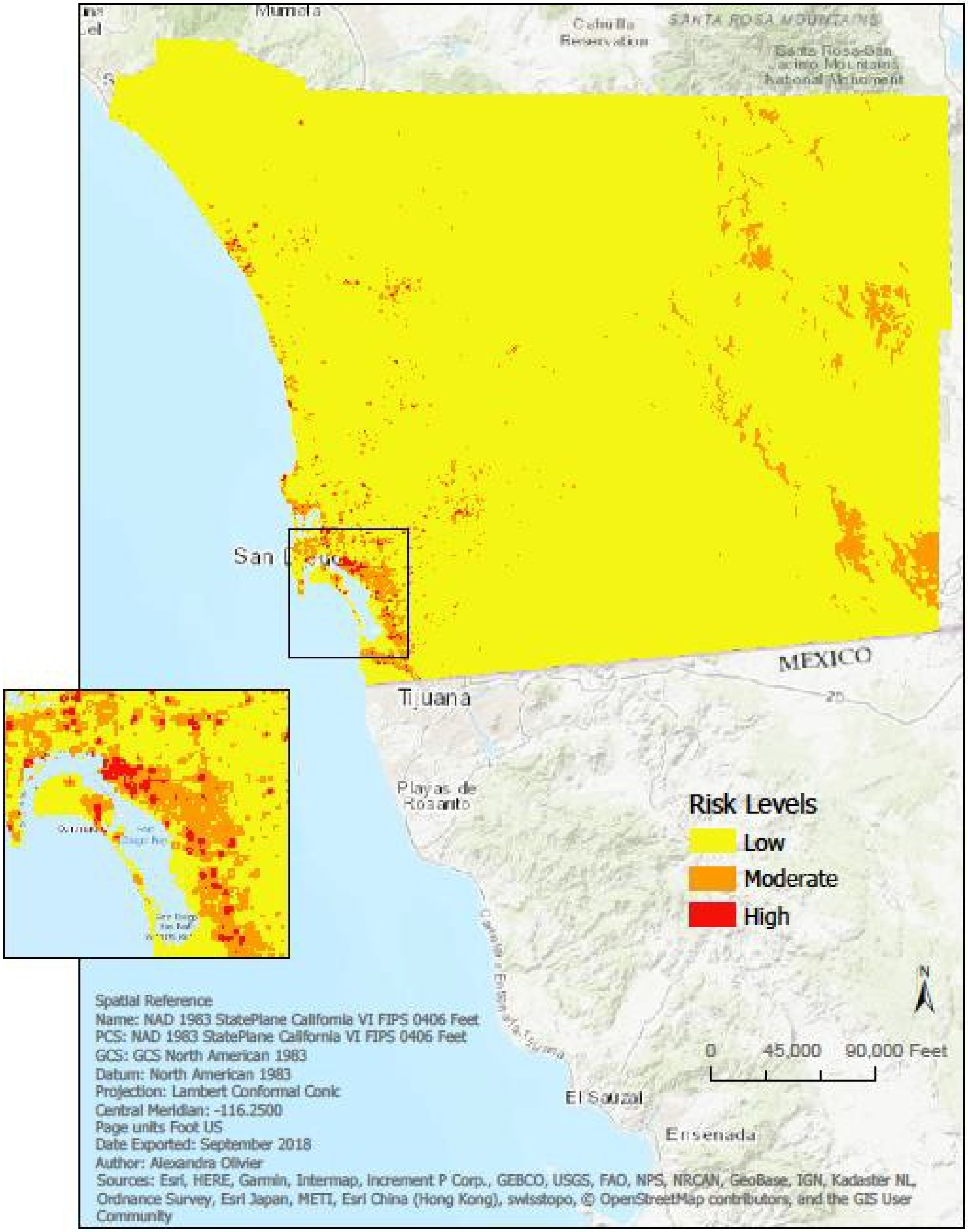

Figure 11. Risk assessment for aerosol dispersal of plague via ground detonation.

Chapter 5 Conclusion and Future Work

In conclusion, risk is indicated for each area in the visualization, but the utmost importance of this information lies within the use to contribute to preparedness planning and mitigation. There are differences in the risk assessment for each pathogen and each method of dissemination. The resulting risk assessment specific to each pathogen shows the areas that are more susceptible to a bioterrorist attack based on multiple factors, such as previous target information and climate data. The use of this information would be advantageous for the appropriate authorities like state or local governments along with the Department of Homeland Security whom are continuously revising preparedness planning and mitigation procedures. The high-risk areas specify where it might be beneficial to drop portable dispensing units in the event of an aerosol bioterrorist attack. Additionally, further analysis would indicate the population density within the area which is useful in determining the amount of supplies to equip the dispending unit with in the event of an attack. While the moderate and low risk zones also represent potential target areas, they should not be ignored. It would be valuable to generate a preparedness and mitigation plan specific to each risk level within the geographic region for each pathogen and dissemination method, taking the appropriate measures dependent upon aspects within the designated region.

Since San Diego has such a high military presence amongst other aspects, people might assume the risk remains high throughout the entire county. However, this analysis demonstrations that there is variation amongst the different biological agents or pathogens and how they are dispersed. There are numerous factors that take part in the success or failure of an attack, environmental variables playing a critical role. Nevertheless, the released biological agent is likely to make either a small or large impact, even though dispersed in a non-ideal climate.

Although, it may not survive for a substantial amount of time it is still possible to infect enough people within the allotted time to be effective. Thus, it may be advantageous to utilize the information acquired from each analysis to shape the preparedness planning and mitigation procedure specific to the impact the pathogen might have on the region specific to dissemination method.

For example, using the results from this analysis one might say that planning for an attack via anthrax should take priority over pneumonic plague and determine the amount of supplies required in a dispensing unit for the risk areas. The high-risk areas would have more supplies delivered in the event of an attack while the moderate and low risk areas may have fewer supplies delivered initially, until otherwise reported. In the case that it is reported, additional supplies can be sent out to the area appropriate to the situation. Also, using this information hospitals and emergency services can prepare with medical equipment and supplies as well as security measures. Along with using for distribution of medical equipment, this type of analysis can also be used to determine security measures and plans for emergency services in the event of an attack. The surrounding buildings, locations, and population density can aid in the safety and organization of distribution of medical equipment in the case of an attack.

There are many uses to this type of data, some of which are focused on in the above summary. The analysis performed here was successful in showing areas of low, moderate, and high-risk areas for an air transmitted bioterrorist attack via aircraft or ground detonation of anthrax or plague. The model can be improved upon by adding more specific datasets relevant to the geographic region that is being observed. The model presented here is not restricted to only San Diego County but is capable of being used in any geographic region, tailoring the datasets to the location.

This risk assessment model indicates low, moderate, and high-risk areas throughout San Diego County for an aerosol dispersed bioterrorist attack using either pathogens to spread pneumonic plague or respiratory anthrax. However, there are areas to further improve upon many aspects to contribute to a more in-depth assessment resulting in improved accuracy to aid with mitigation efforts. In addition to a more detailed assessment, there is also possibilities for development of a specific software program that allows for an efficient assessment of a designated geographic area upon user input of a specific pathogen.

The datasets that may be added to the risk assessment to further pinpoint a specific area and improve accuracy include seasons, temperatures, seasonal wind data, and details that make up San Diego's microclimates. San Diego has four microclimates, coast, inland, mountain, and desert. In each microclimate, the weather varies by factors specific to the area. The coast is characterized with little temperature change and light breezes. During the summer, days are warm but typically cool down in the evenings and fog occurs in spring and early summer. The average temperature range is from 65 degrees to 77 degrees Fahrenheit in summer months. May and June typically involve a thick marine layer in early to mid-mornings, which burns off by midday. The annual average precipitation in this zone is about 10 inches per year, being mostly between November and March (Toner 2013). The coast microclimate would be better for pathogens whose ideal temperature is closer to warm temperatures and more humidity, rather than extremely dry and hot weather.

The types of pathogens that would most likely be prevalent in the inland microclimate of San Diego County are those whose ideal environment involve warm temperatures during the day and cooler temperatures at night, but not below 30 degrees Fahrenheit. The average high temperatures throughout the summertime is 88 degrees Fahrenheit, sometimes reaching 90 degrees or higher. In winter, the inland microclimate becomes cooler than the coastal microclimate and might experience occasional frost. Also, there is more precipitation during the winter in the inland microclimate (Toner 2013). The colder evening temperatures, dry air, and warmer temperatures during the day are not conducive for all pathogens.

Specifically considering these factors to add detail to the assessment could improve the results specific to each pathogen dependent upon their survivability in the specific climate. The summer nights in the mountains microclimate of San Diego County are cooler than the inland and coastal microclimates, with more occasional precipitation in afternoon thunderstorms. The winters in this microclimate are typically cold with snow accumulation. About thirty inches of rain falls within the mountains microclimate per year, compared to the 10 inches a year that the coastal microclimate receives. The average temperatures during the winter range from 35 degrees Fahrenheit to 55 degrees Fahrenheit, whilst the average temperatures during summertime range from 54 degrees to 91 degrees Fahrenheit (Toner 2013). These temperature changes might affect the survivability of the pathogen, in turn decreasing the impact on the designated area and its population.

The desert microclimate in San Diego County experiences extremes of both very hot, dry summers along with cooler winter nights. Desert temperatures experience significant fluctuation between both high and low temperatures. Temperatures in the summer over 100 degrees Fahrenheit while in the winter the lows fall around 43 degrees Fahrenheit (Toner 2013). This microclimate would be ideal for pathogens whose preferred environment is drier, hot weather. Although, due to the variability, some pathogens may only survive during a certain time of day and not others even in the same climate zone.

If desired, individual months can also be considered, taking into account average temperatures within each month, wind speeds, precipitation, humidity, and even popular events that take place across the designated area. Considering average temperatures relative to the time of the assessment can improve results by tailoring specifically to the survivability of pathogens. As mentioned previously, including this information in the analysis would assist with improving the risk assessment model by making it more specific, resulting in improved mitigation and preparation efforts.

In the risk assessment model performed, five climate zones were considered but what was not considered were the detailed temperatures and precipitation specific to the area. Designing a model that is month specific would be advantageous in determining the more vulnerable areas in the event of an attack, aiding in preparedness and mitigation efforts. The information provided by a model such as this would improve results regarding survivability of the biological agents or pathogens. The model would indicate which biological agents would have more of an impact during a specific time of year based on each individual biological agent's survivability. In expanding the environmental variables, it is likely beneficial to consider also evening and night temperatures.

Along with this data, another contributing factor that would improve the model is considering the varying population distribution dependent upon the time of day and whether there are large-scale events occurring. The data used in this analysis takes into consideration the general population and demographic information as distributed by the U.S. Census Bureau. However, the population distribution throughout the county is dependent upon many factors of individual’s everyday lives. People usually migrate to the city areas during the day for work then go home at night, redistributing the population. When there is an event at the conference center in downtown San Diego, this could add an extra 20,000 people to the area which would yield different results. Observing and including reoccurring events such as the ESRI conference or music festivals throughout the county would perhaps improve the accuracy, expanding the scope of possibilities for agencies in charge of preparedness planning. It is likely that accounting for more situations in the analysis would result in better preparedness, response, and mitigation procedures prepared by state, local, or federal departments.

Upon further expansion and improvement of this risk assessment model, there are opportunities to develop a basic software program or web application that would indicate areas that are low, moderate, or high risk for a bioterrorist attack via aerosol. This application could be designed using many biological agents and their accompanying information on survivability rather than only two that were discussed in this risk assessment model. The developer would create a table containing the various biological agents and the climate information of the chosen geographic region, designing the application to run the model upon user input of a specific biological agent. For instance, if the user input was anthrax the application would run both aircraft and ground detonation models to determine the risk areas across the designated region. This input would result in visualizations showing the areas of low, moderate, and high risk across the designated region.

The usages of this application would involve the appropriate authorities whom generate and modify the bioterrorism preparedness planning. Such agencies might include state and local governments, the Department of Homeland Security (DHS), and the Department of Defense (DOD). The resulting visualization of this application would be analyzed to efficiently determine the risk within the area, allowing for concentration of efforts towards improving preparation and mitigation procedures. If an application such as this were developed or improved upon in the case that there is a similar existing application, it would be intelligent to restrict access to only the appropriate authorities and individuals whom use the relayed information to aid in preparedness, planning, and mitigation efforts.

Although the various geoprocessing tools were combined in ModelBuilder to increase efficiency of the process, there is significant room for improvement within the model. Besides additional datasets to improve accuracy of the model, certain adjustments can be made to increase the speed and efficiency. The multiple datasets, some large, within the models can slow down the processing of the data and generation of the resulting visualizations. A suggestion that could be attempted to improve the model is to replace some of the geoprocessing tools with python scripting and to store the data on local memory rather than the hard drive of the computer. As similar as the models are now, they could be combined into one model if desired. However, separating the models per dispersion method and pathogen leaves space for the addition of more datasets specific to the situation, retaining organization and readability of the model.

As a final note, the research and development of this model will continue in order to improve the accuracy and expand the biological agents considered. At this time, the ongoing process will be to manipulate the model and determine any additional datasets required to progress toward other aspects of future work. This includes revisiting the determined methodology and considered environmental variables. Continuing to improve and test the model will aid in the preparedness planning, response, and mitigation strategies by providing information on either attempted or successful methods for determining risk which contributes to further research on the topic.

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