A Spatial Modeling Framework for Siting Critical Supply Infrastructures

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Abstract

Since the launch of the U.S. Department of Homeland Security in 2002, research needs have been established in the areas of disaster preparedness and critical infrastructure protection. Disaster preparedness seeks to lessen the adverse effects of catastrophes by planning in advance and instituting a proper response. Critical infrastructures are those entities deemed necessary for society to function correctly and thus require protection. Recent studies have used location models to aid in the management of many of these crucial establishments. However, few efforts have modeled where to geographically site a future critical supply facility. Furthermore, no research has explored a multi-hazards approach for siting critical supply facilities and the explicitly spatial factors that make a potential target vulnerable to attack. In this article, we propose a strategic multi-objective modeling framework for siting critical supply facilities that incorporates explicitly spatial disaster preparedness directives and critical infrastructure protection demands. We detail the spatial data requirements and modeling assumptions, and present results from an application involving the placement of critical vaccine stores in Orlando, Florida.

Key Words: critical infrastructure protection, critical supplies, disaster preparedness, facility location, vulnerability

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Introduction

In the wake of terrorist events such as those of 11 September 2001 and recent bio-threats such as the 2009 H1N1 pandemic, the ability to protect critical infrastructure and effectively prepare for disasters has become an important element of homeland security and a top U.S. national research priority (White House 2001). Critical infrastructures are those assets that are so vital to the continuity of supplies, service, and communication that their loss would have a debilitating impact on society (Church, Scaparra, and Middleton 2004). Examples of critical infrastructures include vital stockpiles, transportation networks, emergency services, electrical power systems, telecommunications, water supply systems, gas and oil production complexes, chemical plants, defense industrial bases, and other key assets. Since the start of the twentieth century, over one thousand hits against critical infrastructure targets have taken place worldwide (Kosal 2007). The United States has been the target of several high-profile attacks, many of which have focused on major cities. Physical attacks are likely to happen again in the future and critical infrastructure is a likely target (Krieger 1977; Church, Scaparra, and Middleton 2004; Torgerson 2004). Terrorist attacks in the United States and abroad have grown more destructive and can be expected to continue in the future (Savitch and Ardeshev 2001). Consequently, for the sake of infrastructure system continuity, it is beneficial to protect critical assets.

Since the mid-1990’s, the U.S. government has begun initiatives to prepare cities for highly destructive acts of terrorism, especially the possibility of chemical and biological warfare (Center for Disease Control and Prevention 2007). The Centers for Disease Control and Prevention (CDC) have classified biological agents as one of three priority categories for initial public health preparedness efforts (Federal Emergency Management Agency 2005). The CDC recognizes that an extensive aerial release of anthrax, for example, is well within the technological capabilities of foreign or domestic terrorist organizations. (Center for Disease Control and Prevention 2007). In 2003, the CDC reported on the level of bioterrorism preparedness for thirty-four major U.S. cities. The report noted that major U.S. cities were inadequately equipped for dispensing vaccines to their populations (Center for Disease Control and Prevention 2007). As an example, the CDC report shows that a delay in dispensing antibiotics to populations exposed to anthrax will cost many lives. Therein, estimates indicate that if an entire city were exposed to an aerial release of anthrax, a five day delay would result in an 8 percent mortality rate (Center for Disease Control and Prevention 2007). This apparent lack of security and readiness exacerbates the need for a high level of disaster preparedness, particularly for the threat of biological weapons. Clearly the result of such an attack would require communities to supply mass prophylaxis treatment to exposed populations (Federal Emergency Management Agency 2005).

In 2004, the CDC coordinated the Cities Readiness Initiative (CRI), a federally funded effort to prepare major U.S. cities for a large-scale bioterrorist disaster by dispensing emergency supplies to all of the population within forty-eight hours. It is recognized that vaccine supplies can be stockpiled in storage facilities for use in a crucial time of need (Havlak, Gorman, and Adams 2002; Bravata et al. 2006). The Strategic National Stockpile (SNS) is such an implementation on a national scale. However, there is currently no system of critical vaccine stockpiles available on an urban scale. The existence of these facilities would help cities become more prepared to deal with biological threats. The decision of where to locate vaccine stockpiles depends on many strategic and often competing interests. For example, the stockpile may need to be accessible to surrounding populations as well as being placed in a secured location that is not overly exposed to other vulnerable critical assets or potential targets. To address this situation, we propose a multiobjective spatial optimization modeling framework that incorporates disaster preparedness objectives with critical infrastructure protection needs. Specifically, we introduce a Critical Supply Facility Location Model, which seeks to protect critical supplies by maximizing their total weighted distance from all potential targets to each facility and maximizing access to populations by minimizing the total weighted distance of populations assigned to their closest facility. Our methodology builds on existing approaches and extends them to provide potentially efficient and effective solutions for critical infrastructure protection decisions and disaster preparedness needs. The Critical Supply Facility Location Model is potentially applicable to a range of essential supply facilities (e.g. medical stockpiles, water supply systems, gas and oil distribution facilities, power plants, etc.). In this research, we implement the model in a case study where we explore the placement and allocation of critical vaccine stores in Orlando, Florida, a major city added the CRI in 2005. Sample results are given to highlight the trade-offs between facility protection vs. facility access objectives in the model. This is the first known attempt in the literature that seeks locate critical supply infrastructure accounting both for protection issues and supply access. Our modeling efforts should benefit emergency management planners, policy-makers, hazards researchers, and others looking to understand and protect strategic facilities that could be vulnerable to attack.

In this section we have introduced the topic and rationale of the research. The next section gives a review of literature in the fields of critical infrastructure protection, disaster preparedness, and location modeling. The following sections outline the model development and application along with results and conclusions.

Background and Literature Review

Cities are clear targets for terrorist attacks and the entities within them are vulnerable as well (Swanstrom 2002). Over-concentration of potential targets in urban areas partly contributes to their vulnerability. Current conceptual frameworks and advanced techniques to date inadequately address the problem of over-concentration for reducing the vulnerability of potential targets, especially if future potential targets are to be placed. It is argued here that the integration of the spatial aspects of accessibility and vulnerability of critical supply facilities has largely been ignored in the literature. Moreover, the development of methods aimed at managing the spatial aspects of accessibility and vulnerability would fill a needed gap. With the recognition that entities within cities are particularly vulnerable to attacks, this literature review integrates concepts centered on the spatial aspects of accessibility and vulnerability in order to develop a multi-hazards framework for placing critical supply facilities.

Critical Infrastructure Protection

Recognizing that entities within cities are vulnerable to attack, the field of critical infrastructure protection itself has seen recent advancements. Many researchers have focused on identifying critical infrastructures (Church, Scaparra, and Middleton 2004, Amin 2005, Sternberg and Lee 2006). Other researchers have pointed out the challenges and considerations involved with protecting critical infrastructures (see Havlak, Gorman, and Adams 2002; Goodman, Kirk, and Kirk 2007) and have suggested strategies for their management (see Ramberg 1982; Griebel and Phillips 2001; Amin 2005) without proposing explicit formal models or analytical techniques for dealing with these concerns. Wright, Libertore, and Nydick (2006), for example, give a review of modeling efforts in the field of homeland security, including that of critical infrastructure protection. One of their conclusions is that specific applications of spatial models in the area of critical infrastructure protection are lacking, given the range of possibilities for research.

Various conceptual arguments have been put forth in efforts to define specific critical infrastructure protection strategies. For example, energy security tends to be a popular focus because of many other infrastructures' dependencies on power (Amin 2005; Min et al. 2007). Lovins and Lovins (1982), for example, recommend a decentralized energy supply, calling centralized power "the root of the problem" (Lovins and Lovins 1982). Additionally, Lovins and Lovins (1982) recognize that in militarized landscapes, like the Middle East, planners strategically place energy supplies for redundancy and concealment. Ramberg (1982) suggests several strategies for civil and military defense of nuclear reactors, including identifying spatial dimensions of facility protection. Li et al. (2005) introduce an infrastructure defense system for electric power grids. While not entirely focusing on energy protection, The President's Commission on Critical Infrastructure Protection (1997) recognizes that geographical dispersion and redundancy of critical infrastructures assist in providing system continuity if a single entity were interdicted.

Relatively few articles propose explicit models for critical infrastructure protection. In the context of electric grid security, Salmeron, Wood, and Baldick (2004) report on a model that seeks to identify the crucial components in an energy system that when hardened, will yield the best improvement in security. Brown et al. (2006) propose a similar model and apply it to petroleum reserves in Louisiana. It is important to note that these authors use spatial location models to allocate fortification resources, but do not seek to place a future critical facility (e.g. power plants, emergency stockpiles, oil production facilities, chemical plants).

Disaster Preparedness and Response

By definition, disaster preparedness seeks to lessen the adverse effects of disasters and hazards by planning in advance for proper response. This is often done by managing and executing critical supply and relief programs (Larson 2005). In the disaster preparedness literature, researchers seek to strengthen the medical supply (see Klein and Helms 2006), identify challenges (see Havlak, Gorman, and Adams 2002; Need and Mothershead 2006), and suggest strategies for improving public health preparedness (see Bravata et al. 2006).

Some researchers propose explicit mathematical models to pre-position emergency response units and medical supplies. For example, Sathe and Miller-Hooks (2005) put forward an optimization model to locate emergency services close to other critical infrastructures in the case of an emergency. In addition, Farahani and Asgari (2007) implement a multi-criteria coverage model to find the best locations for the least amount of supply facilities in a military logistics system. Jia, Ordóñez, and Dessouky (2007), utilize a similar objective, and apply coverage models for placing medical supplies. What is noteworthy about these efforts is that the models are minimizing the population weighted distance from supplies to demands. This results in maximizing a population's access to a facility by situating a facility as close as possible to the total surrounding populations. However, this can be problematic if the facility is deemed critical itself and needs to maximize its distance from other potential targets. Without this supplemental objective, a critical supply facility may pose a threat to itself and other nearby critical entities.

Location Modeling for Critical Infrastructure Protection and Disaster Preparedness

As suggested by our review of the literature, in recent years, spatial optimization models have been increasingly employed in the problems of homeland security (Wright, Libertore, and Nydick 2006). Location optimization models seek to minimize or maximize some objective, suggesting effective locations of facilities. An example model is the classic *p*-median problem (see Hakimi 1965; ReVelle and Swain 1970; Oppong and Hodgson 1994; Horner and O'Kelly 2005), which seeks to locate a facility by minimizing the total weighted distance from demands to their closest assigned facility (Ghosh and Rushton 1987). The *p*-median problem and its numerous variants are useful in marketing and emergency services provision where a facility's access to people is crucial. A subsequent, opposite approach in single-objective facility location models derives from Church and Garfinkle's *p*-maxian problem (1978), which seeks to maximize the total weighted distance from populations to their assigned facility. This model is used primarily in locating obnoxious facilities (e.g. nuclear power plants, chemical factories, waste disposal sites), where the facilities are essentially undesirable to nearby populations because they expel waste or pollutants (see Erkut and Neuman 1989). In the context of critical infrastructure protection, the *p*-maxian problem is potentially useful for reducing the vulnerability of critical facilities because it can be used to distance new facilities from other existing potential targets.

Location models can be constructed to incorporate both critical infrastructure protection and disaster preparedness objectives. This is important to note, because sometimes the two are inseparable, especially given the competing issues with respect to critical stockpiles. Currently, government programs are actively taking measures to move to an all-hazards approach in planning for disaster preparedness and critical infrastructure protection (U.S. Department of Homeland Security 2007). For example, FEMA (2005) and Larson (2005) consider that because of the recent experience with terrorism, some critical stockpiles should be located away from manufacturers' sites or in multiple locations throughout the country. In addition, Sathe and

Miller-Hooks (2005) suggest locating emergency services close to other critical infrastructures in the case of an emergency.

Clearly location modeling approaches may be incorporated into planning for both critical infrastructure protection and disaster preparedness. The primary nature of these two objectives, however, represents a potential conflict. In disaster preparedness, a primary objective is to minimize distances between population demands and supply facilities, thus maximizing access. In critical infrastructure location, a main objective can be to maximize total weighted distance from potential targets to critical supply facilities in order to maximize facility protection. As a result, a combined, multi-objective model can be proposed to incorporate both dimensions of critical infrastructure protection and disaster preparedness directives for effectively locating a future critical supply facility. Our research incorporates the *p*-median for maximizing accessibility of critical supplies to populations and a variant of the *p*-maxian for maximizing the protection of future critical supply facilities. These models can be fused to form a useful multi-objective spatial optimization framework that fills a major gap in the literature in hazards and homeland security.

Summary of Literature Review

Based on the selected literature, researchers have focused on identifying critical infrastructures and implementing effective techniques to fortify existing infrastructures. These reviewed approaches are potentially inadequate for protecting critical infrastructure. Resilience in fortification measures is limited (Amin 2005). With recent advancement in weapons development, even the most hardened building is vulnerable (Krieger 1977). In addition, hardening critical infrastructures with fortification resources may be economically infeasible and an attempt to fortify all of them with physical materials is impractical. Subsequently, with limited fortification resources, other inexpensive alternatives for protecting critical infrastructures become viable options.

Researchers have implemented effective techniques for managing emergency supply preparedness and response. However, none of the techniques reviewed incorporate the potential problems of a critical supply being too accessible or too close to other potential targets such that the facility/facilities are vulnerable to attack. The existing literature does not effectively address the problems of placing a future critical supply facility with regard to the explicitly spatial, simultaneous problems of accessibility and vulnerability. We propose a new method of managing future critical infrastructures by utilizing spatially explicit characteristics on the accessibility and vulnerability of potential targets. Further, the use of this modeling framework will effectively address the identified spatial problems associated with accessibility and vulnerability of critical supply facilities; issues that have not been previously accounted for.

Methods

Decision makers are usually faced with a number of different factors that influence the location of a facility (Daskin 1995). In the context of critical facilities, security is an important consideration in determining locations. In regards to relief supply points for disaster preparedness, surrounding populations are essential in determining their locations. So in the sense of placing critical stockpiles, security and access to surrounding populations are the two basic factors that should influence their locations.

To satisfy the goals of objectively suggesting locations for new critical supply facilities, locational parameters, potential costs and constraints must be represented mathematically in an optimization model. We present a formulation that minimizes total weighted distance of populations to their closest assigned facility (maximize accessibility) and maximizes total weighted distance from sited facilities to all potential target areas (maximize facility protection). The model introduced may be viewed as an extension to the *p*-median problem that is widely found in the facility location literature (Hakimi 1965; ReVelle and Swain 1970; Oppong and Hodgson 1994). The undesirable facility location literature is useful for positioning the proposed modeling approach, particularly for the requisite trade-off between access and protection. Undesirable facility location problems seek to locate facilities as far from populations as possible in order to minimize the menace associated with such facilities (Church and Garfinkle 1978; Erkut and Neuman 1989). One example of such a location problem is the aforementioned *p*-maxian, where the weighted distances from a facility are to be maximized from some demand vector (i.e. potential targets). We use a variant of the *p*-maxian because we are interested in minimizing system-wide vulnerability with the placement of future facilities. This can be accomplished by maximizing total weighted distances from *all* potential targets to *each* sited facility. This is different from the *p*-maxian because we account for all potential interactions between facilities and potential targets rather than just the targets and their assigned closest facility. However, critical infrastructure facilities are not necessarily entirely undesirable. These facilities are more appropriately classified as semi-desirable, where they may pose a threat (they are the target of attack), but are desirable for populations so they should be as close to populations as possible. Subsequently, a variant of the *p*-maxian will be used to employ the trade-off goal of protection against the goal of access; this is the key element in developing the multi-objective Critical Supply Facility Location Model.

The Critical Supply Facility Location Model

Minimize

$$Z_1 = \sum_{i}^{n} \sum_{j}^{m} P_j D_{ij} X_{ij} \tag{1}$$

Maximize

$$Z_2 = \sum_{i}^{n} \sum_{j}^{m} V_j D_{ij} Y_i \tag{2}$$

Subject to

$$\sum_{j}^{m} X_{ij} = 1, \forall_i = 1, \ldots, n \tag{3}$$

$$Y_i - X_{ij} \geq 0, \forall_{i,j} \text{ and } i \neq j \tag{4}$$

$$\sum_{i}^{n} Y_i = f \tag{5}$$

$$Y_i + Y_k \leq 1, \forall_i, k \in \Phi_i \tag{6}$$

$$X_{ij} = 1,0, \forall_{i,j} \tag{7}$$

$$Y_i = 1,0, \forall_i \tag{8}$$

Where

i, k = index of potential facility sites
n = Set of all potential facility sites
j = index of demand nodes
m = Set of all demand nodes
D_{ij} = Distance matrix between potential facility site *i* and demand node *j*
P_j = Vector of population
V_j = Vector of vulnerabilities or potential targets
f = User specified number of facilities to be located
R = User specified minimum interfacility distance
$a_{ik} = \begin{cases} 1 \text{ if potential facility site } i \text{ is within } R \text{ distance of site } k \\ 0 \text{ if otherwise} \end{cases}$
Φ_i = set of potential facility sites in conflict with site *i*
$\Phi_i = \{k \mid a_{ik} = 1\}$
Y_k = Facility location where $k \in \Phi_i$ is too close to Y_i
Y_i = Facility location; $\begin{cases} 1 \text{ if facility is located at node } i \\ 0 \text{ if otherwise} \end{cases}$

X_{ij} = Decision variable; $\begin{cases} 1 \text{ if demands at node } j \text{ are served by facility at node } i \\ 0 \text{ if otherwise} \end{cases}$

The multi-objective problem stated above combines the two previously established modeling objectives. The first equation (1) is essentially the *p*-median problem in that it seeks to minimize total weighted distances from population demands assigned to their closest facility, thus maximizing access to emergency supplies. The second equation (2) is similar to the *p*-maxian problem in that the trade-off objective seeks to maximize total weighted distances from *all* potential targets to *each* facility, thus maximizing system-wide protection. Constraints in (3) stipulate that each population demand node on the network is assigned to be served by exactly one facility. Constraints in (4) require population demand nodes to be assigned to a node only where a facility is opened up. Constraint (5) limits the number of facilities, *f*, to be located to a number specified by the user. Constraints in (6) are pair-wise restrictions, ensuring facility locations Y_i and Y_k are not within a standard distance *R* of each other where $k \in \Phi_i$. Constraints in equation (7) are binary constraints, stating assignments are made, *one,* or otherwise not, *zero.* Constraints in equation (8) are also binary constraints, stating that a facility is either to be located, *one*, or otherwise not, *zero*. The decision variables include the facility location and the allocation of a facility's resources to population demands. The location of a facility, Y_i, is ascribed a *one* if the facility is located at node *i*; *zero* if otherwise. The allocation of a facility's resources to population demands, X_{ij}, is ascribed a *one* if the demands at node *j* are served by a facility at node *i*; *zero* if otherwise.

In terms of the relationship of our model to existing approaches, we combine two well-known spatial models (*p*-median and a variant of the *p*-maxian) into a multi-objective problem used to address trade-offs between access and protection. While no other researchers have developed such a model in the context of hazards, there have been other, related efforts that use multiobjective models to reduce facility impacts on populations. For example, Murray et al. (1998) develop a hybrid location model utilizing the *p*-median and a coverage modeling framework for siting undesirable facilities (e.g. waste disposal) to maximize the total weighted population that is not impacted by a facility site in addition to minimizing the total weighted distance of populations to assigned service facilities.

Study Area

Our model is applied in the context of the state of Florida. In terms of population, Florida is the fourth largest state (eighteen million people), and based on recent data, had the third highest rate of growth within the United States (U.S. Census Bureau 2006). The U.S. Census (2006) urbanized estimate for the state was at 84 percent and is eighth in the United States in population density (Caruson and MacManus 2007). Florida's vulnerability to attack has been a concern of several researchers and local government officials in Florida. According to a study done by Caruson et al. (2005), Florida has a higher than average vulnerability to attack ranking as compared with the rest of the United States in terms of population and the built environment. According to another study by Caruson and MacManus in 2007, the state's own assessment affirms that the potential for terrorist attacks remain high (Caruson and MacManus 2007).

In this research, we analyze the Orlando metropolitan area in the central region of Florida. The estimated population of the Orlando metropolitan area is nearly two million people (U.S. Census Bureau 2006). Home to several world famous theme parks like Walt Disney World and Universal Studios, Orlando attracts a sizable portion of the forty-eight million tourists that visit Florida annually (Caruson and MacManus 2006). Alongside Jacksonville, Orlando ranks as the most vulnerable cities in Florida in terms of the likely physical targets they contain (Caruson et al. 2005). In 2005, Orlando was added to the CRI (Center for Disease Control and Prevention 2007).

Data

Finding optimal critical supply facility locations necessitates an analysis of the potential location points and its surrounding demands (e.g. human populations) and repellants (e.g. vulnerable areas, potential targets, etc.). In this case, the potential facility location points must be able to serve all the population while having their locations constrained to areas less vulnerable to attack. Areas vulnerable to attack include places with important entities and are a function of their relative degree of spatial clustering. These vulnerable entities can be buildings, monuments, skilled/educated populations, tourist destinations, and notable cities (e.g. capitols) (Sternberg and Lee 2006). Vulnerability, in this case, is determined by the number of potential targets associated with each observation unit (i.e. node/centroid). In this research, critical facilities are used as a proxy for potential targets since critical facilities are likely targets. This attribute multiplied by the distance to a potential facility location serves as the parameter to each decision variable. Thus our goal is to maximize the total weighted distance from facility locations to potential targets, thus reducing the risk to a future critical facility at a potential site location.

A potential limitation to this research, or any other work, is how one defines vulnerability. There are other potential factors that might impact the vulnerability of an entity to attack, including, but not limited to the following: 1) Hardening of building through physical construction materials. 2) Architectural design and layout of both the building and the perimeter (e.g. allometry) (Griebel and Phillips 2001; FEMA 2005). 3) Security initiatives such as guards, locks, and passwords. 4) Geographical/spatial positioning of critical assets (dispersion, redundancy, decentralization, deconcentration). These four major factors should have direct impact on the vulnerability of critical entities. With the consideration of these four approaches, we are primarily focused on the last factor: geographical/spatial positioning of critical assets.

For this model application, we use individual critical facilities aggregated to the census tract level to define a vector of vulnerability/potential targets for the study area (see Figure 1). Population data from the 2000 U.S. Census are also aggregated to census tracts for the study area (see Figure 1). There are 268 census tracts in the study region. The centroid (geometric center) of the census tract is used to represent the location of the population of people P_i and critical facilities V_i within each census tract. In context of the model, the centroid then serves as a node which will either hold an opened critical supply facility or is served by a node which contains such a facility.

[Insert Figure 1 about here]

There are several established indicators that are useful for determining a critical facility, including the type of building, location, type of construction, number of occupants, and economic life (Federal Emergency Management Agency 2005). In addition to those listed, we include the size of the building as an indicator of criticality. Based on the guidelines established by FEMA (2005), we filtered a comprehensive database of critical facilities from the InfoUSA 2007 database using relatively conservative filter levels (See Table 1). The majority of these critical facilities are located near the urban center of Orlando.

[Insert Table 1 here]

The hypothetical scenario we model assumes an airborne attack on critical facilities and that goods are distributed from critical facilities to populations over road networks. Thus, in our application, we use two different distance matrices. First, the spatial separation between a candidate vaccine facility location and other potential targets (D_{ij}) is measured in Euclidean distances (see Figure 2). The rationale behind this is we are assuming an airborne attack for this particular model application, and airplanes are not restricted to road networks, so they are able to fly directly from point to point, thus straight line distances are most appropriate. Second, the separation between candidate locations and population demands is measured using network distances. These separations can either be measured in straight line or network distances, depending on how the supplies are delivered, which will depend on the nature of the analysis. In 2001, a twelve hour push package of emergency supplies from the SNS was delivered by a combination of air and land vehicles (Need and Mothershead 2006). If they are sent by truck, network distances should be used since they would travel by road. If they are delivered by air, they should be measured by straight line distances. In this case, network distances are used since the most likely mode of transport within an urban area would take place on a road network. Of course, in any future policy-oriented work, the analyst would be free to choose whatever distance metric they felt best represented the context of the scenario.

[Insert Figure 2 here]

Scenario: Facility Access vs. Facility Protection

We propose a hypothetical situation in which a planner would like to locate a critical vaccine supply facility taking into consideration protection for the facility. Ideally, the decision maker would like to minimize vulnerability and maximize access; however that creates conflicting objectives in the context of the model. Consequently, it is necessary to construct scenarios that reflect different policy objectives—one that emphasizes access in contrast to vulnerability, and vice versa. Exploring different policy scenarios allows for an evaluation of alternative solutions and would possibly help decision makers determine the consequences of various actions (Cohon 1978; Bravata et al. 2006). As a result, we investigate alternative solutions by using the weighting method which is employed in the objective function to allow the user to adjust how much weight each objective should be given relative to the other and explore the trade-offs in the model (see Malczewski 1999).

In fact, given the problem has two objectives, the most direct way of solving it is by using the weighting method where w is the user specified weight on the objective and $0 \le w \le 1$ (Horner and Downs 2007). This allows for the two objectives to be combined into a single objective, Z_c, such that

$$Z_c = w(Z_1) - (1-w)(Z_2) \tag{9}$$

To solve the multi-objective problem, the conflicting objectives are then combined into a single weighted objective (9), with the maximization objective subtracted from the minimization objective and solved for a range of user-defined weights, w (Wu and Murray 2005).

The spatial data were managed in ArcGIS 9.2 and Excel. C++ was used to compile the spatial data into linear programming files that contain the mathematical model of equations (1-8) and our spatial data. The linear programming files were then imported into CPLEX 11.0, an optimization engine, and solved for various weights on the proposed objectives. Results were then exported back into ArcGIS 9.2 and Excel for data visualization and further analysis. This was carried out on a Pentium 4, 3.2 GHZ processor machine running Windows XP on 16 gigabytes of RAM.

The Critical Supply Facility Location Model in the Orlando metropolitan area was run with f at one and five facilities with a variation of weights for each number of facilities. Generation of a Pareto-optimal set can be derived by systematically changing the weight, w, and solving equation (9) (Wu and Murray 2005). Generally speaking, the weights were run through increments of 0.1 to generate a range of solution alternatives to illustrate the trade-offs of the problem. All solution values (i.e. facility location configurations) found were optimal given the prescribed weights.

Results

Graphical and cartographic displays are shown in Figures 3, 4, and 5 to help visualize the results. Figure 3 shows graphs of the Pareto-optimal objective values of Z_1 (access) and Z_2 (protection) to help evaluate the trade-offs the model provides. Pareto-optimal solutions are those which are not dominated by others in the solution space of two or more objectives. A Pareto-optimal solution exists if "…no other feasible solution yields an improvement in one objective without causing a degradation in at least one other objective" (Cohon 1978). Some interesting trends take place in the graphs that should be mentioned. First, at $f = 1$, the trade-offs are fairly direct with a slight bend in the trade-off curve towards the Z_2 objective. For example, at $f = 1$ and $w = 0.26$, there is a 37 percent gain in protection with a 30 percent sacrifice in access (see compromise location in Figure 5). This means there is a very slight gain in protection while sacrificing access as the weight increases on Z_2. At $f = 5$, substantial gains become more apparent as the trade-off curve becomes more steep. This suggests that when placing multiple facilities, substantial gains in the trade-offs become more pronounced. For example, where $f = 5$ and $w = 0.8$, there is a 49 percent gain in protection while only 10 percent of access is lost (see compromise locations in Figure 5).

Figure 4 are selected cartographic displays of the results of facility locations and allocations of resources to demands. As seen in Figure 4, at $f = 1$ and $w = 1$, the facility is placed near downtown Orlando, thus having minimized access to surrounding populations. At $w = 0.000001$, the facility is placed on the fringe of the urban periphery where its weighted distance is maximized. Figure 5 shows cartographic displays of facility locations where $w = 1$

(maximizing access), *w* = 0.000001 (maximizing protection), and *w* is a compromise weight in between access and protection (i.e. *w* = 0.26 at one facility and *w* = 0.8 at five facilities).

The trade-off curves can be explained by a few factors. The first of these is the distribution of the population relative to the critical facilities in Orlando. It appears that critical facilities and the human population have a strong spatial correlation; however, critical facilities tend to cluster in the central downtown area, while populations cluster outside of the downtown area in the suburban periphery. So in a sense of placing a facility, the model finds Pareto-optimal locations with respect to the spatial form of the surrounding populations and critical facilities. This is one reason for the why the trade-offs appear in this manner.

Second, the trade-off gains may also be explained by the allocations of resources to demands. With a compromise weight on objective Z_1 and Z_2, the model seeks to find Pareto-optimal solutions without concern for supply limitations at each facility. This may result in the amount of resource allocations from an accessible facility to be far greater than resource allocations from a less accessible, farther away facility since Z_1 seeks to minimize its weighted distance to population demands and Z_2 seeks to maximize its weighted distance to potential targets. This would potentially cause an overburden of supply relative to demand at the most accessible facility/facilities. For example, at *f* = 5, the model can find a Pareto-optimal solution by allocating resources from one facility at the center of the population with the other facilities maximizing its allocations from critical facilities by being placed on the edge of the graph. This allows the model to find a best compromise between access to populations and protection from other critical facilities, thus creating objective values with substantial trade-off gains.

[Insert Figure 3 here]

[Insert Figure 4 here]

[Insert Figure 5 here]

Summary and Conclusions

In summary, the trade-offs of access and protection among a single facility are fairly direct, meaning a compromise in access is nearly equal the gain in protection. However, for multiple facilities, the trade-offs in this model application show more substantial gains in the protection objective when compromising access. This indicates that locating multiple facilities for emergency supplies will not only allow for redundant supply, but will also allow for some protection to be gained for a fractional loss in access. Although the trade-offs may not be great among one facility, given the actual size of a facility in relation to a census tract, having a 1 percent gain in protection could have a considerable influence on the distance to other potential targets. For example, a 1 percent gain in protection might possibly place a facility in one census tract at a sufficient enough distance from a vulnerable area that is subject to an attack, thus allowing for a potentially satisfactory solution. One limitation to our approach is that a facility may only need to be placed a certain distance from any other potential target. This type of approach would clearly require a different set of objectives and constraints in the context of protecting critical infrastructures. This is left for further research.

The modeling approach presented in this research illustrates key elements that are needed to locate future critical supply facilities. Clearly, critical infrastructure protection and disaster preparedness can have conflicting objectives. However, multi-objective optimization can help illustrate possible Pareto-optimal locations for facilities of this nature and provide best compromise solutions subject to objective parameters.

It is also important to note that these results are used for model illustration and are not intended for use in policy decisions. The model explored in this research may need further refinement or modification for specific policy applications. For example, constraints entailing facility costs or supply limitations were not modeled; future work may wish to take these and other ideas into consideration. In addition, the case of vaccine stockpiles should be accessible to medical professionals qualified to administer the vaccines, which would entail expanding the definition of accessibility we have employed in this model application.

Critical infrastructure protection has been deemed an important research area for the twenty-first century. Alternative avenues of thought and methods can lead to new problem solutions. As our discussion suggests, urban concentrations are more spatially vulnerable compared with more dispersed types of settlement patterns. Based on this assumption, our research gives some theoretical insight into critical supply facility location with regards to facility protection. In particular, we present a new model that builds on and extends existing models to incorporate critical facility clustering as a modeling parameter to act as a repellant for future critical facilities, thus serving as a spatial technique for protecting critical supply facilities.

Disaster preparedness for human-made attacks remains pertinent as a result of recent terrorist actions (Federal Emergency Management Agency 2005). Bio-warfare, in particular, has been an increasing concern and proposing an optimization approach to siting emergency supplies as has been done here can help minimize casualties or disruptions that could occur in urban areas. In addition to maximizing the total weighted distance from other critical facilities for the protection of a critical supply facility, we incorporate the human settlement structure of an urban area to act as an attractor for emergency supply facilities so that a population’s access to a supply facility is maximized. Specifically, we combine these two objectives into a Critical Supply

Facility Location Model, a general multi-objective model used to site future critical supply facilities, which is solved for various weights on each objective where a facility's potential location is Pareto-optimized. Overall, the broader implications of this work include setting a conceptual foundation for locating future critical supply facilities, including articulating and modeling the competing interests of protecting and making critical stockpiles accessible. We would anticipate future work in the area would extend our methodology to new applications areas and alternative modeling scenarios.

In conclusion, this approach has shed new light on the spatial structure of critical facilities and urban populations (and their subsequent spatial dimension of vulnerability) with how they interact as interdependent parts of an emergency infrastructure network. The Critical Supply Facility Location Model this research introduces presents a multi-hazard approach for strategically siting future critical supply facilities and incorporates new spatial techniques for planning the locations of critical supply infrastructures.

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Table 1. Criticality Indicators.

Criticality Indicator	Measure	Filter Level
Type of Building	Standard Industrial Classification (SIC)	Critical SIC codes*
Location	Address/Coordinates	None (all distances used)
Type of Construction	Material	Not available
Number of Occupants	Employee Count	> 25
Economic Life	Dollar Assets and Income	> 1,000,000
Building Size	Square Footage	> 10,000

Note: Critical assets were determined by binary user-specification, where the filter level represents a quantity for which a facility is deemed critical or not. 1 = critical, 0 if otherwise.

* See Maliszewski (2008) for the SIC codes used in this study.

Figure 1. Maps of population density and potential target density in Orlando, Florida. *Source:* InfoUSA (2007) and U.S. Census Bureau (2000).

Figure 2. Strategic critical vaccine supply diagram. Network distances are used to measure the separation between stockpiles and population demands. Euclidean distances are used to measure the separation between stockpiles and potential targets.

Figure 3. Pareto-optimal results of the Critical Supply Facility Location Model in Orlando, Florida f = 1 (A) and f = 5 (B). The numeric labels indicate percentage of protection gained, and percentage of access lost.

Figure 4. Maps of facility locations/allocations (f = 1, 5) in Orlando, Florida where w = 0.000001 and 1. Note: The links shown in Figure 3 should not be used to interpret allocation routes; rather, they are assignments from a stockpile to demands.

Figure 5. Maps of facility locations (f = 1, 5) in Orlando, Florida. Compromise weights w shown are 0.26 at f = 1 and 0.8 at f = 5.

Figure 1.

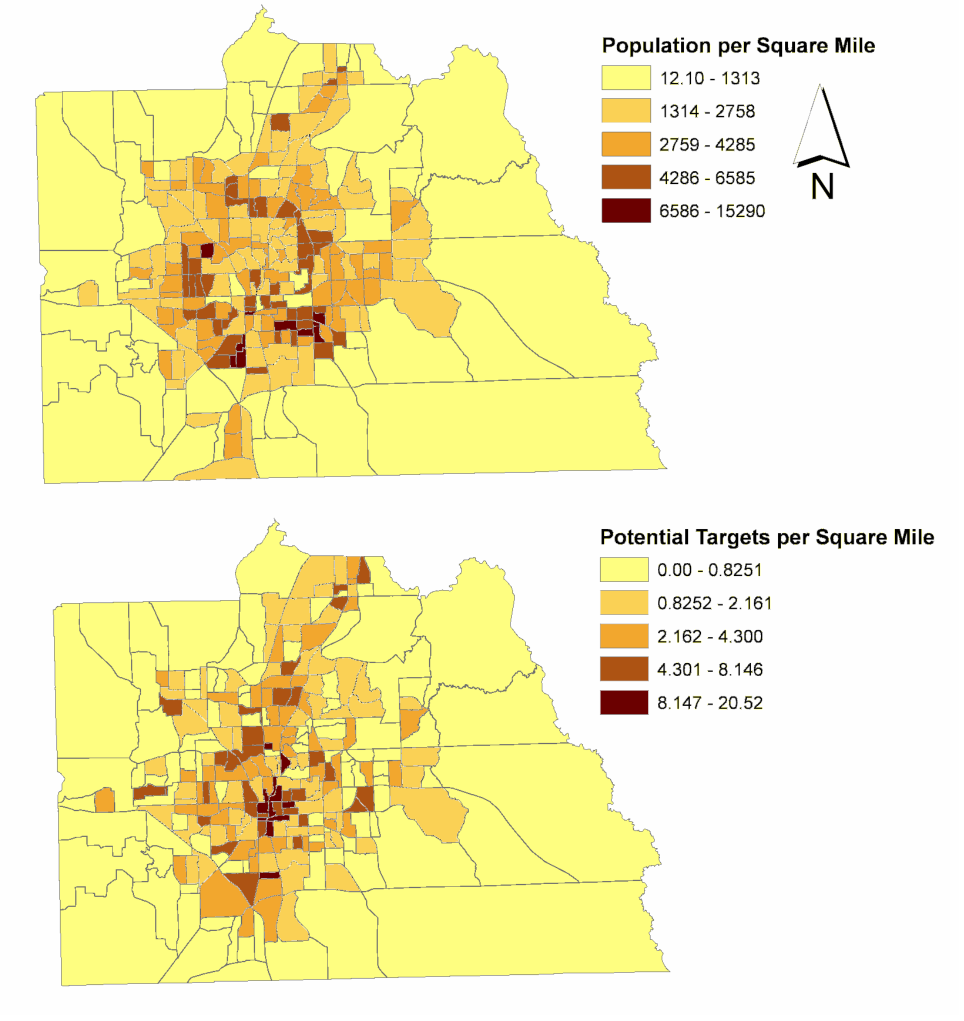

Population per Square Mile
12.10 - 1313
1314 - 2758
2759 - 4285
4286 - 6585
6586 - 15290
N
Potential Targets per Square Mile
0.00 - 0.8251
0.8252 - 2.161
2.162 - 4.300
4.301 - 8.146
8.147 - 20.52

Figure 2.

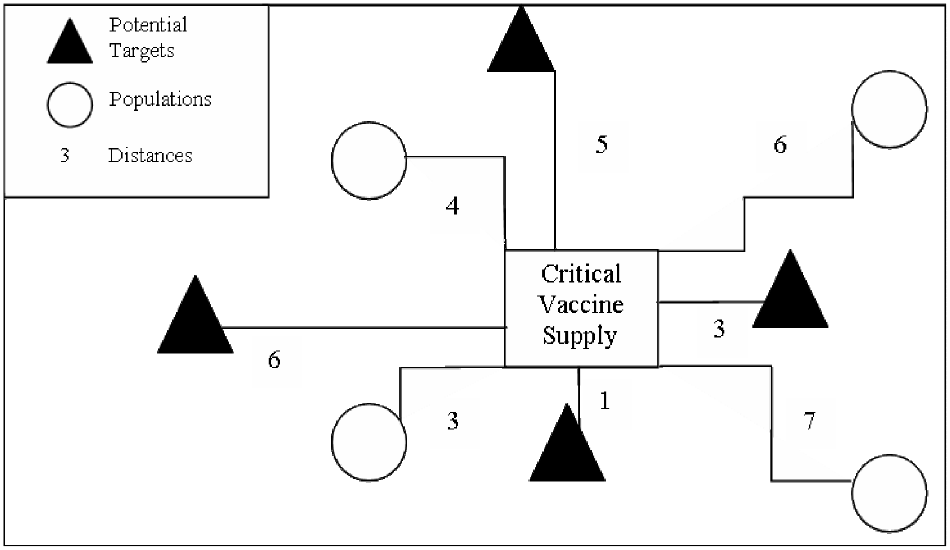

Potential Targets
Populations
3 Distances
Critical Vaccine Supply
5
6
4
3
6
3
1
7

Figure 3.

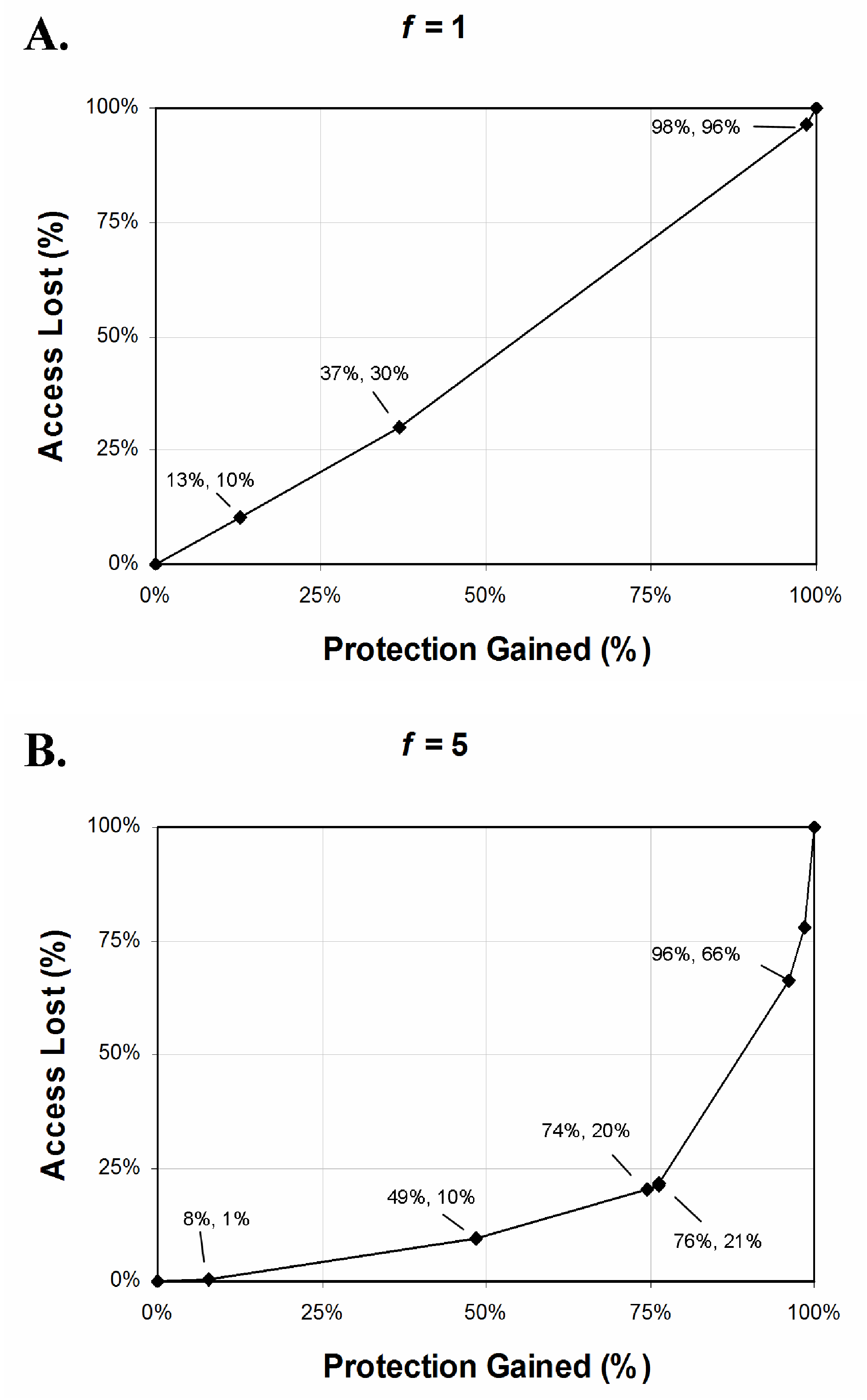

A.
f = 1
100%
75%
50%
25%
0%
Access Lost (%)
98%, 96%
37%, 30%
13%, 10%
0%
25%
50%
75%
100%
Protection Gained (%)
B.
f = 5
100%
75%
50%
25%
0%
Access Lost (%)
96%, 66%
74%, 20%
49%, 10%
8%, 1%
76%, 21%
0%
25%
50%
75%
100%
Protection Gained (%)

Figure 4.

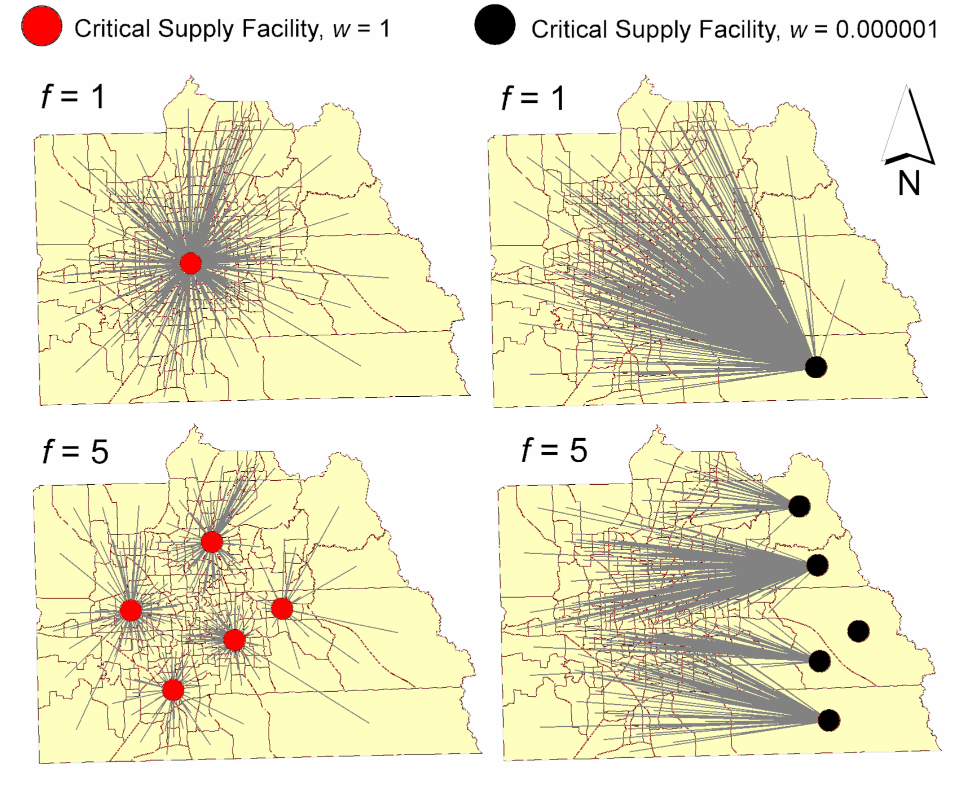
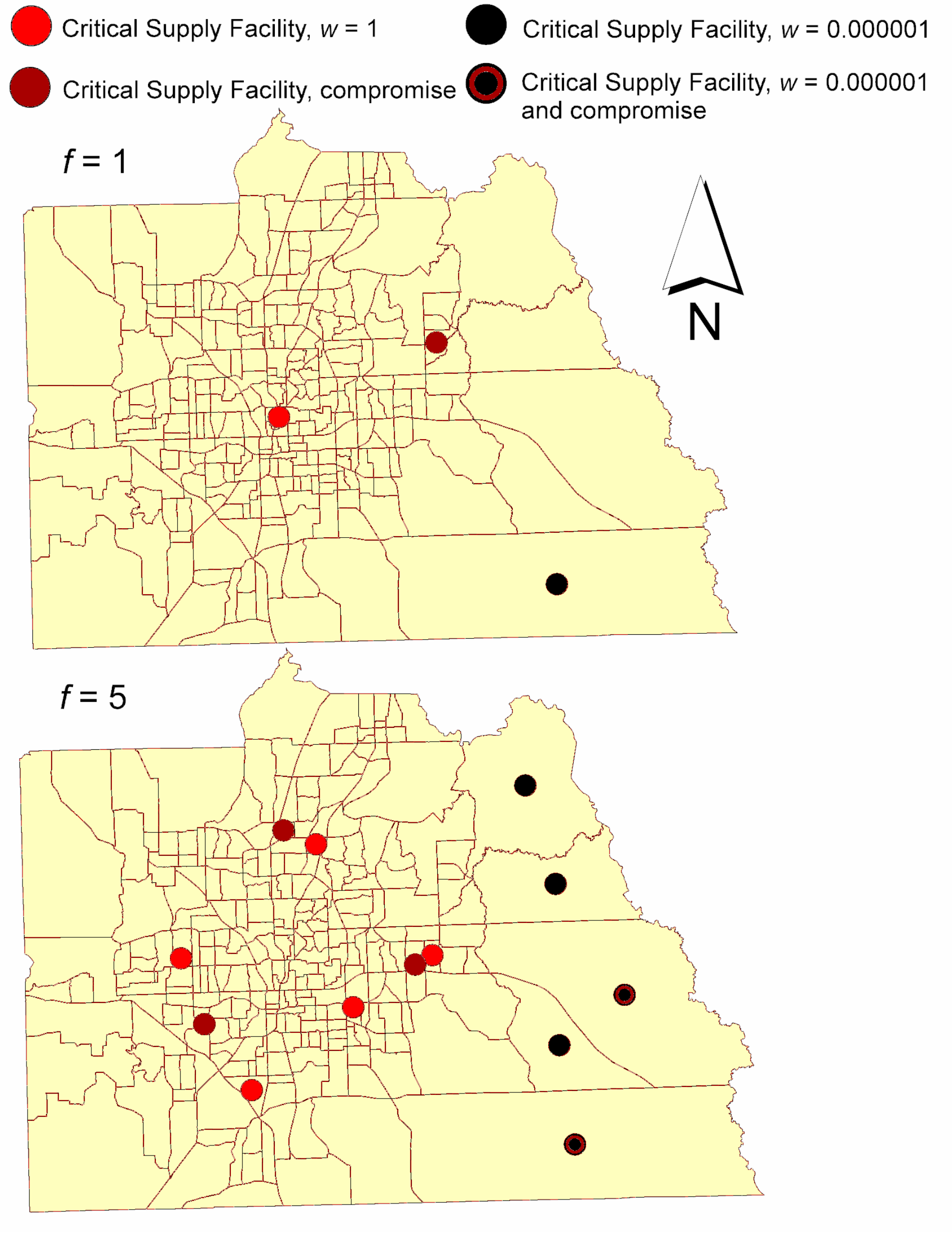

Critical Supply Facility, w = 1
Critical Supply Facility, w = 0.000001
f = 1
f = 1
N
f = 5
f = 5

Figure 5.


Critical Supply Facility, w = 1
Critical Supply Facility, w = 0.000001
Critical Supply Facility, compromise
Critical Supply Facility, w = 0.000001 and compromise
f = 1
N
f = 5