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Preparing for Out of Hospital Cardiac Arrests (OHCA) in Riyadh, Saudi Arabia: A GIS Scenario-Modeling Approach

by

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Dissertation

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Dedication

This dissertation is dedicated to my parents, my loving wife Nada, and my three kids (Mohamed Ali, Omer, and Osman), brothers, sisters, and relatives. They are all looking forward to see the completion of this research.

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The help and encouragements I received from my parents and my brothers and sisters are greatly appreciated. My parents, I love you and thank you for being my role models. No words can express my deepest gratitude to you: without you there, there is no me. Infinite gratitude and appreciation are due to my wife and my three kids for their sacrifice, moral support, and financing of this research. I also want to extend my greetings and appreciation to my wife’s parents for their moral support and encouragement. Special thanks are extended to my lovely sister Rawya and her husband, Waeil, for their infinite support, generosity, and taking care of my kids whenever I need them.

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Above all, I render my thanks and praise to Almighty Allah, who offered me all things to accomplish this work.

Abstract

This study employed location-allocation modeling and a geographic information system (GIS) to study the current placement of automated external defibrillators (AEDs) in relationship to neighborhoods in Riyadh City, Saudi Arabia, and to determine the optimal locations for additional AEDs in the city. Using GIS to mathematically locate additional healthcare facilities for the placement of AEDs is more reliable than to select them using informed guesses. The objective of this research was to elaborate a mathematical and GIS model for placing AED devices so that people who need to use these devices in the City of Riyadh, Saudi Arabia, can access them within a time frame of three minutes or less, which is the international standard for such accessibility. The research employed street blocks as demand points; existing healthcare facilities, mosques, and schools as supply points; and the maximum coverage algorithm to model optimal locations for AED devices. Models were run for both vehicle and pedestrian travel times. Model results of current conditions indicated that 75% of household blocks were covered when vehicles were used to access AED sites, as compared to 9% of people when pedestrian travel to an AED is considered. Introduction of 1,371 mosques and 34 community colleges and universities as additional supply points for AEDs improved coverage to 94% for vehicular access, but only 34% for pedestrian traffic. Although mosques are considered to be focus points for Muslim communities, other facilities including, but not limited to, police stations, malls, primary and secondary schools, and playgrounds should be used to gain wider coverage. In addition, cluster analysis should be employed to avoid selecting AED supply points that are too close to each other and which are unlikely to improve accessibility. The study succeeded in elaborating a framework for conceptualizing the relationship between vehicular and pedestrian access to AEDs. It also demonstrates how GIS-based location-allocation modeling can be used for efficient placement of AEDs. The broad conceptual framework for AED placement used in this study has applicability to other countries in the Middle East.

Table of Contents

List of Tables

Page

List of Figures

List of Abbreviations

ACLS	Advanced Cardiac Life Support
AED	Automated External Defibrillator
CPR	Cardiopulmonary Resuscitation
ECGs	Electrocardiograms
EMS	Emergency Medical Services
ESRI	Environmental Systems Research Institute
GIS	Geographic Information System
HCF	Healthcare Facility
KSA	Kingdom of Saudi Arabia
OHCA	Out-of-Hospital Cardiac Arrest
PAD	Public Access Defibrillation
SCA	Sudden Cardiac Arrest

Chapter 1: Introduction

Background

Sudden out-of-hospital cardiac arrest (OHCA) is defined as the cessation of cardiac mechanical activity, confirmed by the absence of signs of circulation, away from a hospital environment (McNally et al., 2011). While there is a notion that cardiac arrest and heart attack refer to the same condition, they are actually two different medical conditions. Heart attacks, or myocardial infarctions, refer to the lack of blood flow to arteries due to a waxy substance that builds up inside the coronary arteries (Mehta, Curwin, Gomes, & Fuster, 1998). Cardiac arrest, on the other hand, is a sudden stop in effective blood circulation due to failure of the heart (Schwetterle & Duranton, 2014). The focus of this study is on cardiac arrest occurring outside of a hospital situation, i.e., OHCA.

A geographic information system (GIS) can be combined with statistical/mathematical models and data from comprehensive cardiac arrest registries to produce maps that highlight regions, cities, and communities that are at varying risk for cardiac arrest (Semple et al., 2013). In addition, GIS can provide information on contiguous areas of high and low bystander cardiopulmonary resuscitation (CPR) rates with the aim of more effectively targeting intervention and eventually reducing cardiac deaths (Raun, Jefferson, Persse, & Ensor, 2013).

In many countries, mortality from sudden out-of-hospital cardiac arrest is among the most common contributors to total mortality (Krizmaric, Verlic, Stiglic, Grmec, & Kokol, 2009); hence, the disease has been widely studied.

If OHCA is treated properly and early, it is potentially reversible, but the survival rates of patients who suffer from OHCA are relatively low. Larsen, Eisenberg, Cummins, and

Hallstrom (1993) found that a one minute delay in time to first shock in OHCA could lead to a 7—10% decrease in the chance of survival. For patients who are treated with a defibrillator, the possibilities of surviving sudden cardiac arrest were three times higher inside a hospital than outside it (Sakamoto et al., 2014). Chances of survival of an OHCA are improved with more rapid response times of ambulances (Wright, Bannister, Ryder, & Mackintosh, 1990) and/or increase with early defibrillation and broad dissemination of automated external defibrillators (AEDs) and CPR for use by nonmedical volunteers (Capucci et al., 2002, p. 1065).

Chain of Survival

The chain of survival refers to a progression of activities that, when put into movement, decreases the mortality related to heart failure (Bossaert, 1997). The chain is shown in Figure 1. According to American Heart Association (2015), the five links in the adult out-of-hospital chain of survival are as follows:

- recognition of cardiac arrest and activation of the emergency response system,
- early cardiopulmonary resuscitation (CPR) with an emphasis on chest compressions,
- rapid defibrillation,
- basic and advanced emergency medical services,
- advanced life support and post-cardiac arrest care.

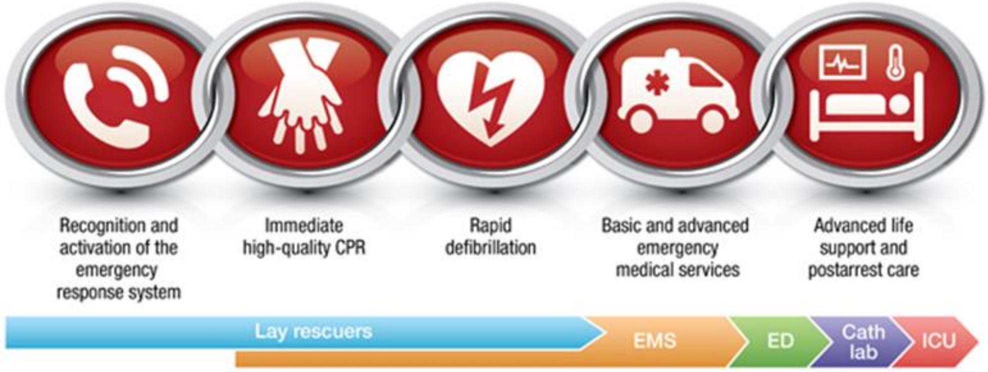

Figure 1. Chain of survival for out-of-hospital cardiac arrest (OHCA). Note. American Heart Association. (2015). Highlights of the 2015 American Heart Association guidelines update for CPR and ECC, Copyright 2017 by Copyright Holder. Reprinted from: https://cpr.heart.org/, with permission.

Measures needed to strengthen the chain of survival include speedy activation of emergency medical services (EMS), prompt bystander involvement in CPR, early defibrillation, and timely advanced cardiac life support (ACLS; Cummins, Ornato, Thies, & Pepe, 1991). Ambulances are one of the most important steps in the chain of survival. The extensive training of emergency staff can save the lives of OHCA patients due to fibrillation (Wright et al., 1990, p. 600). To fight sudden cardiac arrest (SCA), Arntz, Mochmann, and Breckwoldt (2013) and Mancini et al. (2010) state that education of patients and relatives, and the necessity of basic life support are essential. The prognosis among patients who suffer from OHCA is currently poor, so an effort to increase the survival rate is a necessity (Morrison et al., 2006). Early CPR is essential because it can prevent severe brain damage due to the lack of blood flow to the brain (Krizmaric et al., 2009).

To increase the survival rates, effort should focused on timely involvement of bystanders and EMS personnel (McNally et al., 2011). AEDs should also be placed at optimal locations. For example, they can be placed in schools (Das, & Zipes, 2003; Mosesso, 2013; Swor, Grace, McGovern, Weiner, & Walton, 2013), airplanes (Goodspeed & Lee, 2009; Page et al., 2000), and airports. AEDs in schools protect students as well as people whose age places them at greater risk, such as adult employees and others who volunteer or contribute at community events at the school.

In the previous guidelines, the general approach to CPR was “A-B-C”: airway, breathing, and circulation (Field et al., 2010). The new 2015 AHA guidelines for OHCA recommend an inverted sequence of chain of survival “C-A-B”: compressions, airway, and breathing. The survival of OHCA increases if the five steps of the chain of survival is implemented early (Cummins et al., 1991). Much clinical evidence suggests that bystander involvement at the point of care, through the provision of CPR and administration of AEDs, noticeably increases the chances of survival from OHCA (Larsen, et al. 1993; Vaillancourt & Stiell, 2004). Therefore, ‘*early’* is the key word for all steps of the chain of survival to increase survivability.

Statement of the Problem

In the Middle East, incidences of OHCA are increasing (Irfan et al., 2016). Also, policies aimed at improving the coverage of AEDs to cater for out-of-hospital cardiac arrest patients are being implemented without a strong empirical and analytical foundation, particularly at the neighborhood level where the problem is most evident. Both anecdotal evidence and perceptions of the geographic pattern of the disease derived from studies carried out in Western countries play a large role in guiding attempts to mitigate against OHCA in the Middle East. This is unacceptable because anecdotal evidence is often far from reliable. In addition, Western geographic patterns of the disease may not repeat themselves in the Middle East.

In recognition of these problems, this study employed location-based analysis to study the relationships between the present location of AED devices and the location of the population centers to develop a framework that can be used to determine the optimal placements for AEDs in Riyadh, Saudi Arabia, and perhaps other Middle Eastern countries.

Summary of Research Approach

This study demonstrates the use of GIS and network location-allocation modeling as a means for guiding the placement of AEDs. The goal was to plan for improving the odds of surviving OHCA in Riyadh by evaluating current AED availability and identifying potential additional locations for public access defibrillators using GIS modeling. Implementing a framework for deploying AEDs in different locations within the neighborhoods was used in order to improve the survivability of OHCA victims.

Significance of the Problem

Based on a review of the available literature, this study is the first of its kind for Saudi Arabia. The goal was to identify potential locations for public access defibrillators in Riyadh using GIS-based location-allocation modeling.

Notwithstanding the policy of the Saudi government to promote the use of AEDs and CPR training, such policies tend to be more effective when they are informed by knowledge and understanding of the geographic pattern of OHCA victims, particularly at community or neighborhood levels. Such an understanding could improve policies targeting responses to OHCA intervention activities and can save lives and millions of dollar in health resources. In

Riyadh, 96% of potential OHCA patients have died in the field or on their way to a healthcare facility (Arabi et al., 2013a), so implementing a framework to achieve reachable AEDs in different locations within the neighborhoods will improve the survivability of OHCA victims. Automated external defibrillators (AEDs) are designed to be used by the public. They have become widely available, safe, and friendly use. Adequate training in CPR and use of AEDs is an important component of increasing the OHCA survivability. Even though, the use of AEDs was not restricted to trained personnel, it is highly desirable that those who may be called upon to use an AED should be trained and their qualifications are kept up to date.

In the US, Canada, and Europe, distinctive historical, social, and economic processes have given rise to certain geographic patterns of OHCA outcomes. However, it cannot be inferred that such geographic patterns and processes completely exist in the Middle East. Therefore, an understanding of the relationship between the distribution of OHCA in this world region and patterns of accessibility to healthcare services are necessary in order to inform policy-makers and health practitioners of communities that are likely to be at high risk for OHCA. This research seeks to contribute to an understanding of this problem in one Middle East country, Saudi Arabia.

At the time of this study, the infrastructure for collecting OHCA data at the community level in Saudi Arabia was not well developed, including the system for home addressing. Also, there was no common repository for OHCA data obtained from various sources, and various designs and standards are used to collect data. In addition to analyzing the distribution of AEDs for OHCA survivability, this research makes specific actionable recommendations on how the Riyadh can improve access to the chain of survival and decrease OHCA mortality.

Objective of the Research

The objectives of this study are as follows:

1. Determine existing time-distance accessibility to public AED devices for different neighborhoods by calculating point-and network-based service areas for pedestrian and automobile travel.
2. Use location-allocation modeling to study the spatial efficiency of existing placements of AEDs in relation to demand centers.
3. Use location-allocation model to make recommendations as to the optimal placements of AEDs given the OHCA situation in Riyadh.

Research Questions

1. What is the current level of accessibility to hospitals and other healthcare facilities for potential OHCA patients in Riyadh?
2. Is Riyadh appropriately covered with AEDs to save OHCA victims?
3. What are the optimal locations for the placement of AEDs in Riyadh, and how many additional AEDs are needed to maximize coverage of AED accessibility in Riyadh?

Delimitations and Limitations

- The Census data was downloaded from the website of the general authority for statistics in Riyadh (https://www.stats.gov.sa/en). Data from the 2014 census were used for this study.

- Riyadh has many different types of healthcare facilities, including hospitals, private clinics, medical clinics, and primary care units. This study focused on hospitals, medical clinics, and primary care units. Private clinics were not included.
- The geographic factors in this study are limited to the Riyadh.
- The study focused on only one type of heart disease, namely out-of-hospital cardiac arrest (OHCA).

Key Terms

- *Advanced cardiac life support* (ACLS) is emergency medical procedures in which basic life support efforts of cardiopulmonary resuscitation are augmented by establishment of an IV fluid line, possible defibrillation, drug administration, control of cardiac arrhythmias, endotracheal intubation, and use of ventilation equipment.
- *Automated external defibrillator* (AED) is a device that examines the rhythm of the heart, and in the event that it distinguishes an issue that may react to an electrical stun, it discharges electricity to reestablish a typical heart rhythm (Barkley, Johnson, & Olson, 1998).
- *Cardiac arrest* is the cessation of cardiac mechanical activity as confirmed by the absence of signs of circulation (McNally et al., 2011).
- *Cardiopulmonary resuscitation* (CPR) is a potentially lifesaving procedure where the chest that is overlying the heart is compressed mimicking a beating heart. This artificial circulation maintains blood flow when the heart stops due to multiple causes, specifically trauma, disease, or even drugs (AHA, 2015).

- *Early electrocardiograms* (ECG) is a recording of the heart's electrical activity via an electrocardiograph machine that is plotted over time (Gibler et al., 1990).
- *Geographic information system* (GIS) is a computer application used to store, view, and analyze geographical information, especially maps. (i.e. health outcomes, risk factors, disease outbreak, earthquake assessment, population distribution, medical care).

Organization of Dissertation

This dissertation is organized into six chapters. The following is the structure and outline of each chapter: Chapter 1 provided an introduction to the study and a statement of the problem. It also discussed the nature and significance of the problem, the objectives of this research, and limitation of the study. Chapter 2 examines the causes and symptoms of cardiac arrest, responds to OHCA, geographic patterns of OHCA, review of OHCA work in the Middle East, and the nature of location-allocation modeling. Chapter 3 provides a detailed description of the methodology, research design, and data collection and processing**.** Chapter 4 reports on the results of the data analysis. Chapter 5 summarizes the key findings of the study, and a strategy for improvements is also proposed. Chapter 6 presents conclusions and recommendations of the study.

Chapter 2: Review of Literature

Immediate usage of AED increases the percentage of survival rate. It has been estimated that “90% of OHCA patients recovered in the first minute, 50% in the fifth minute, 30% in the seventh minute, 10–12% in the tenth minute and about 2% up to the twelfth minute” (Seraj, 2006, p. 3). In other words there is decrease of 7–10% in OHCA survivability for every minute delay in using AED. Notwithstanding the critical importance of AEDs for saving life, the number and location of devices available in Riyadh is unknown (Berhanu Al Nasser, 2012). Globally, one third of deaths each year are from cardiovascular diseases.

Although previous public health studies involving AEDs have been done for Saudi Arabia (Berhanu & Al Nasser, 2012), none have been found that investigated accessibility to AEDs in the largest city in Saudi Arabia. This research attempts to fill this information gap. This chapter provides a summary of the relevant literature related to this study.

Causes and Symptoms of Cardiac Arrest

The heart pumps blood to the majority of the body's organs. In the event that the heart stops working (acute myocardial infarction), blood flow stops, and organs start to close down, and within a few minutes the individual will die. In the event that cardiovascular failure is recognized and treated promptly, genuine organ harm, brain damage, or death can be avoided. Cardiovascular failure can happen in adults and children. It can happen abruptly in an individual who was thought to be healthy (Torpy, Burke, & Glass, 2006). Torpy et al., (2006) listed a few causes of cardiac arrest:

- myocardial infarction (heart attack);
- some kinds of arrhythmias (abnormal heart rhythms);

- severe blood loss from traumatic injury or internal bleeding;
- electrical shock injury;
- lack of oxygen supply from events like choking, drowning, or a severe asthma attack;
- cardiogenic shock (heart failure because of inadequate heart pumping function);
- stroke (sudden loss of blood supply in the brain);
- heart valve or heart muscle disease;
- certain genetic disorders that affect the heart.

Out-of-hospital cardiac arrest (OHCA) has also been connected to exposure to particulate air contamination (Rosenthal et al., 2013).

When cardiac arrest happens, the individual becomes lethargic and oblivious to his/her surroundings. There is no heartbeat, no circulatory strain, and no breathing. In the event that an electrocardiogram is carried out, there is either no electrical movement from the heart or a heart rhythm, (for example, ventricular fibrillation) that does not deliver successful heart function (Torpy et al., 2006). Chugh et al. (2008) stated that “the presence of left ventricular hypertrophy (LVH) is a strong independent risk factor for future cardiac events and all-cause mortality” (p. 436). Herlitz, Svensson, Engdahl, and Silfverstolpe (2008) listed six criteria that increased chance of survival: increasing age, witnessed arrest, bystander CPR, cardiac arrest outside home, shorter ambulance response time, and need for defibrillatory shock.

Responding to OHCA

Cardiovascular failure remains a significant reason for death in all parts of the world (Torpy et al., 2006). To improve OHCA prevention and resuscitation, a better understanding of variability in needed, since the disease varies around the globe (Berdowski, Berg, Tijssen, & Koster, 2010). To improve outcomes, Clumpner and Mobley (2008) recommended that practitioners focus on the basics of resuscitation: frequent CPR training, dispatcher-aided CPR and rapid EMS response, treating patients where they lie, 20 minutes of CPR before ambulance transport, good scene management, and “pit crew” CPR.

Ong et al. (2011) distinguished five potential methods for enhancing survival rates for OHCA:

1. Widespread community-based and systemic endeavors to expand bystander CPR.
2. Investment in public access defibrillation (PAD).
3. Having an essential life support Emergency Medical Services (EMS) framework.
4. Developing Advanced Life Support (ALS) EMS systems.
5. Putting resources into hospital-based post resuscitation care (cardiac arrest centers).

This research focuses on investing in public access to existing AEDs by providing guidelines for deploying AEDs to achieve maximum coverage of AEDs in Riyadh.

Geographic Patterns of Out-of-Hospital Cardiac Arrest (OHCA)

The geography of OHCA has been studied at different spatial scales, including global, regional, national, inter-city, metropolitan-wide, community, and household levels.

In North America, the United States alone accounts for 300,000 to 400,000 OHCA deaths annually, i.e., close to 1,000 deaths per day (Rosamond et al., 2008; Zipes & Wellens, 1998). An average annual incidence rate in the US in 2000 was 250 per 100,000 as compared to 350 per 100,000 in 2010. Approximately 92% of persons who experience an OHCA event die (McNally et al., 2011). In the US, the survival rates of OHCA increased from 5.7% in the reference period of 2005–2006 to 7.2% in 2008 to 8.3% in 2012 (Chan, McNally, Tang, & Kellermann, 2014) even though Sasson, Rogers, Dahl, and Kellermann (2010) stated that survival from OHCA has been stable for the last three decades (7.6%).

In Europe, out-of-hospital sudden cardiac arrest is a leading cause of death (Atwood, Eisenberg, Herlitz, & Rea, 2005) with around 350,000 people dying each year from the disease (Gräsner, Böttiger, & Bossaert, 2014). The survival rates in Central Europe range from 9.5% in Bohemian region, Czech Republic (Pleskot et al., 2006), to 11% in Dachau, Germany (Estner et al., 2007), and 22% in Maribor, Slovenia (Grmec, Strnad, & Podgorsek, 2009). In Northern Europe, the OHCA survival rates range from 6% in Nottinghamshire, England (Soo et al., 1999), to 11% in Copenhagen (Steinmetz, Barnung, Nielsen, Risom, & Rasmussen, 2008) and 13% in Tampere, Finland (Kämäräinen, Virkkunen, Yli-Hankala, & Silfvast, 2007; Hiltunen, et al., 2012).). In Western Europe the survival rates range from 9% in Amsterdam (Waalewijn, de Vos, & Koster, 1998) to 7% in France (Agostinucci et al., 2011). For the southern part of Europe the survival rates range from 10% in Pordenone province, Italy (Kette et al., 2007), to 6% in Netherlands (Bardai et al., 2011).

In Eastern Asia the survival rates range from 0.6% in Yamaguchi, Japan (Shiraki et al., 2009), to 1% in Tai Pei, Taiwan (Hu, 1994), 2.3% in Korea (Ahn et al., 2010), and 3% in Osaka, Japan (Iwami et al., 2007).

In Western Asia and Middle East region survival rates ranged from 6.1% in Jerusalem (Ginsberg, Kark, & Einav, 2015) to 7.2% in Bahrain (Mohamed & Daylami, 2005), and

21.4% in Cyprus (Karagiannis, Georgiou, Kouskouni, Iacovidou, & Xanthos, 2012). In South-East Asia, the OHCA survival rates range from 0.9% in Singapore (Ong et al., 2008) to 9.5% in Malaysia (Chew, Idzwan, Hisamuddin, Kamaruddin, & Wan Aasim, 2008).

In Australia the survival rate range from 6% in Queensland (Woodall, McCarthy, Johnston, Tippett, & Bonham, 2007) to 13% in Sydney (Flynn, Fugaccia, Thanakrishnan, Milliss, & Cheung, 2006).

OHCA at the sub-regional level within countries. Within individual countries significant spatial variation in the disease outcome has been observed. In the United States, survival rates ranged from 0.2% in Detroit, MI (Dunne et al., 2007), to 7.7 in Alabama and 39.4% in Seattle (Nichol et al. 2008; Berdowski, et al. 2010). In Canada, survival rates ranged from 4% in Montreal (Vaillancourt & Stiell, 2004) to 6% in Toronto and 10 % in Vancouver (Nichol et al., 2008). In Italy, the OHCA survival rates varied from 6% in Piacenza (Capucci & Aschieri, 2011) to 10% in Pordenone (Kette et al., 2007). In Scotland, it varied from 8% in Glasgow to 13% in Edinburgh (Rainer, Gordon, Robertson, & Cusack, 1995). In Germany, the survival rates decreased from 14% in Heidelberg (Böttiger et al., 1999) to 11% in Dachau (Kentsch, Schlichting, Mathes, Rodemerk, & Ittel, 2000; Estner et al., 2007). In Japan, the survival rate range from 0.6% in Yamaguchi (Shiraki et al., 2009) to 1% in Okayama City (Hayashi & Ujike, 2005). In Australia, the survival rate range from 6% in Queensland (Woodall et al., 2007) to 13% in Sydney (Flynn et al., 2006). In Sweden, the number of OHCA survival has nevertheless increased over the past decade, and victim of sudden cardiac arrest is saved generally once every six hours the survival rates of OHCA increased from 12.7% in 1992 to 22.3% in 2005 (Hollenberg et al., 2008).

OHCA at the city level. At the city level, it is not entirely clear if OHCA survival rates vary considerably by size of cities. For instance, for small cities (population < 1 million), the survival rate in Doha is 34.6% and 42.3% for female and male, respectively, (Arabi, Patel, Alsuwaidi, Singh, & Albinali, 2013), and in Nottinghamshire (county in the East Midlands of England), the out-of-hospital cardiac arrest survival was poor despite the presence of the ambulance crew. Only 44.3% made it to the hospital (Soo et al., 1999). In Edinburgh, capital city of Scotland, Rainer et al. (1995) declared that the survival rate was 8.2%. By contrast, in Rotterdam the survival rates were 88%, 81%, 77%, and 73% for 1, 3, 5, and 7 years of follow-up, respectively. They declared that age, gender, and diagnosis were significant predictors of survival. In Boston, 22% survived initially, and 3.8% survived for the hospital discharge (Murphy, Murray, Robinson, & Campion, 1989), and in Denizli, Turkey, the survival of OHCA was 11.2% (Erdur et al., 2008).

For a medium size city (8 million < population >1 million) the survival rates is 0% in the city of Queretaro (Berdowski et al., 2010), Beirut, 5.5% (El Sayed, Tamim, Nasreddine, Dishjekenian, & Kazzi, 2014). In Shiraz, Iran, there were no significant differences between genders in terms of survival rates (0.4%; Bolandparvaz et al., 2009). In Johannesburg, the survival rates was 40% (Stein, 2009), and Seattle, which has nearly same number of population, the survival rates was 10% for the elderly versus 14% of the younger patients (Longstreth, Cobb, Fahrenbruch, & Copass, 1990).

For the large city (population > 8 million), the OHCA survival rates recorded by ambulance services in London, England, was 31.7% (Cowie, et al. 2000). In Belgium, Calle et al. (1997) reported the survival rate of OHCA was 21%, and in New York, was 1.4% (Lombardi & Gallagher, 1994).

OHCA within cities. Within individual cities, considerable variations have been observed in the spatial pattern of OHCA. In general, lower income communities have higher incidence rates compared to higher income communities (Sasson et al., 2012). For example, in Rochester, New York, Lerner, Fairbanks, and Shah (2005) noted that communities with OHCA hot spots were communities with lower median income and where many people lived below the poverty level. In addition, most of the victims were African American, without a high school diploma. Merchant, Becker, Yang, and Groeneveld (2011) evaluated OHCA survival rates for Blacks compared with Whites. They found that survival rates for Blacks were lower than Whites. Shah, Shah, and Bhopal (2014) also investigated racial/ethnic differences in terms of OHCA in the US. They reported that Black OHCA victims were less likely to receive bystander CPR, have an initial ventricular fibrillation, or have a witnessed arrest. Moreover, Blacks had lower survival rates following hospital admission and discharge.

Cowie, Fahrenbruch, Cobb, and Hallstrom (1993) studied the relationship between Black/White racial groups and OHCA survival rates in Seattle. They found mortality of Black victims was twice as great as in White people, and the initial resuscitation rate was significantly worse in the Black patients as well as after hospital discharge. In New York City, the age-adjusted incidence of OHCA was higher among Blacks, and the survival was higher among Whites (Galea et al., 2007). African American and Latino OHCA victims were younger than Caucasian in Los Angeles (Benson, Eckstein, McClung, & Henderson, 2009). There were no significant differences between Middle Eastern Arabs and South Asians when Arabi, Patel, Alsuwaidi, and Singh (2013) calculated OHCA survival rates.

OHCA at the community and household level. Within communities, studies have shown that OHCA occur more frequency in homes compared to public spaces. Approximately 70% of the OHCA occurs in residential areas (Ong et al., 2008; Folke et al., 2010). To increase the survivability of OHCA, Kwon et al. (2016) suggested allocating AEDs in each household and in each notable spot in an open space. This suggestion is acceptable if the AED device price is affordable and the study area is small and not populated. However, in the US, survival from OHCA is higher when it happens outside the home (27%) versus inside (13%; Litwin, Eisenberg, Hallstrom, & Cummins, 1987). Also, most of the cases pertain to younger men. In Hong Kong, Chung and Wong (2005) stated that 63.9% of OHCA cases occurred at home, 12.5% in hotels, and 2.8% outdoors. In the Detroit area, statistically there was no significance difference between races, even though the socioeconomic status for the Whites victims were more likely to be above median household income (Sayegh et al., 1999) when they studied OHCA. In South Glamorgan (Wales), more than 65% of OHCA cases occurred in private homes, and 44% were unwitnessed. Of the 13% that occurred in the street, only 28% were unwitnessed (Weston, Jones, & Wilson, 1997). In London, England, approximately 80% of OHCAs occur at home and 20% in public places (Newman, Mosesso, Ornato, & Paris, 2002). In community-wide studies, overall survival rates ranged from 4 to 33% depending on the chain of survival (Kuilman, Bleeker, Hartman, & Simoons, 1999; Eisenberg & Mengert, 2001; Bunch et al. 2003).

Out-of-hospital cardiac arrest not only affects older people but also children. Sirbaugh et al. (1999) performed a study targeting children less than 17 years of age with OHCA symptoms in a large urban municipality. The majority of the victims were male. Black children occupied the top position followed by Hispanic children, and the White children came at the end in terms of frequency of OHCA, with most of the cases occurring at home.

Review of OHCA Work in the Middle East

In the Middle East, the literature review revealed little research on the geography of OHCA. Excluding the research done by Arabi et al. (2013), Roth et al. (2000),Ginsberg et al. (2015), El Sayed et al. (2014), and Erdur et al. (2008), none of the papers cited in the previous sections looked specifically at OHCA in the Middle East. One of the few studies that touched on OHCA in the Middle East was done by Conroy and Jolin (1999), who studied OHCA in Riyadh from 1989 to 1995. The study was based on only 95 patients and estimated the OHCA incidence among adults (20 to 100 years old). The authors stated that "survival to hospital discharge from out-of-hospital cardiac arrest was 5.1% for adults and 7.4% for children" (Conroy & Jolin, 1999, p. 617). In the Gulf region, limited data surrounding OHCA has been published. Except for Dubai, no OHCA information has been published for the rest of the six Emirates in the UAE. The goal of this study was to report patient characteristics and outcomes of all OHCA cases in the Northern Emirates. In the total of 384 OHCA victims, only 0.5% of cases were able to access and apply defibrillators, and there was 30% rate of bystander cardiopulmonary resuscitation being performed (Batt, Al-Hajeri, & Cummins, 2016).

In the Kingdom of Saudi Arabia (KSA), despite the lack of statistics on broad OHCA patterns, the use of automated external defibrillator (AED) and cardiopulmonary resuscitation (CPR) training is becoming widespread (Berhanu & Al Nasser, 2012). Healthcare workers in Saudi Arabia are required to participate in recertification in advanced cardiac life support (ACLS) every two years. ACLS certification includes being proficient in CPR, being able to interpret significant early electrocardiograms (ECGs), and proficiency in the use of AED devices (Berhanu & Al Nasser, 2012). The KSA depends on data about resuscitation outcomes and factors affecting the outcome from the US and Europe (Aldawood, 2007). In Riyadh, the rate of mortality after OHCA is high. It is unknown whether this rate will decrease if laypersons are trained to attempt defibrillation with the use of AEDs (Berhanu & Al Nasser, 2012). Conroy and Jolin (1999) stated the outcome reflects the level of out-of-hospital care available in the city. Recent studies have demonstrated low survival rates for cardiac arrests in Saudi Arabia (Berhanu, & Salleeh, 2015).

Geographic Information System (GIS) and OHCA

Applications and techniques in GIS have been used extensively in OHCA research including, but not limited to developing of web applications for visualizing and analyzing community OHCA patterns (Semple, Qin, & Sasson, 2013), identifying high-risk communities for unattended OHCA (Semple et al., 2013), identifying census tracts with high risk of OHCA (Nassel et al., 2014), identifying census tract with high incidence of OHCA (Lijovic et al., 2014), finding optimal installation locations for AEDs (Huang & Wen, 2014; Ban, Fredman, Jonsson, & Svensson, 2013), and determining which ambulance can quickest respond to an event (Park et al., 2016).

Location-Allocation Modeling

Location-allocation modeling is a form of optimization modeling. Its basic goal is to select the optimal location for *m* facilities from an arrangement of *n* competing facilities where $m < n$, and at the same time, allocate demand to the facilities in the most efficient way (Fotheringham, Densham, & Curtis, 1995).

Location-allocation modeling can be traced back to the work of Alfred Weber (1909), who considered the issue of how best to locate a warehouse to minimize the aggregate travel distance between the warehouse and an arrangement of spatially distributed clients. These models have been well researched since the 1960s (Reagan Jr & Foust Jr, 1960; Getz & Ryan, 2005; Lei, Church, & Lei, 2016; Chapman, 2016) and have been used widely either for finding optimal locations or for evaluating existing locations (Ghosh & Harche, 1993). For example, it has been used to guide the placement of facilities such as fire stations (Meyer, 2011), waste disposal sites (Min, Jayaraman, & Srivastava, 1998), locations exchange in a telephone network (O'kelly, 1986), and health service development (Rahman, & Smith, 2000).

Each location-allocation model contains three fundamental components: demand locations, facility locations, and a distance and/or time matrix holding distances or traveling time between services facilities and demands locations (Farahani, SteadieSeifi, & Asgari, 2010). The goal is to select optimal locations from a set of facility locations in the most efficient manner and assign them to demand locations based on the spatial distribution of demand for the service (Algharib, 2011).

Demand is normally defined as the number of persons likely to use or need a service and is typically represented as a set of polygons or centroids of polygons with the associated attribute data. Facility locations are also represented in the model as a set of points. A matrix is used to hold the various distance values between demand and candidate locations. Distance between locations is typically assumed to be the least travel cost distance between places.

Since a location-allocation model is essentially an objective function that should either be minimized or maximized subject to certain constraints, then the decision to minimize or maximize the function depends on the goal of the location-allocation problem. For instance, the goal could be to minimize travel cost or distances between supply points, maximize service coverage in an area, maximize capacitated coverage, minimize the number of facilities to be sited, or maximize attendance at facilities (Brandeau & Chiu, 1989).

There are many types of location-allocation modeling algorithms. These include the p-median algorithm (Hakimi, 1965), maximize coverage (Poduri & Sukhatme, 2004), maximize capacitated coverage (Owen & Daskin, 1998), minimize facilities (Hodgson, 1978), maximize attendance (Mirchandani & Head, 2001), maximize market share (Goodchild, 1984), and target market share (Inderst & Shaffer, 2010).

The *p*-median solution, proposed by Hakimi (1965), is perhaps one of the most well-known location-allocation algorithms. It is used when the goal is to select optimal locations for *p* facilities such that the total weighted travel distance between demand nodes and facilities are minimized. With this algorithm, facilities are located based on distance such that the total weighted cost between demand and solution facilities is minimized between all demand points (Hakimi, 1965). This problem type is traditionally used to locate warehouses (Perl & Daskin, 1985), airports (Min, 1997), and health clinics (Rahman & Smith, 2000), and the goal is to minimize travel time to the location of fixed facilities.

The maximize coverage algorithm is used when the goal is *to select* demand points within a predetermined response time. Maximize coverage chooses facilities such that as much demand as possible is covered before an impedance cutoff (Poduri & Sukhatme, 2004). Maximize coverage has been used widely to locate facilities such as fire stations (Algharib, 2011; Meyer, 2011), police stations (Cheung, Yoon, & Chow, 2015), and pizza delivery facilities (Marianov, Vladimir, & Daniel, 2002).

The maximize capacitated algorithm is similar to the maximize coverage algorithm. However, the constraint of capacity is added to the model, meaning facilities can be allocated demand beyond their capacity. Also, impedance cutoff is not required (Current & Storbeck, 1988). The capacity of the facility is assigned before running the model, which captures the demand point that has maximum weight (e.g., locating hospitals with a limited number of beds).

The minimize facilities algorithm minimizes the number of facilities selected while covering as many demand points as possible within the impedance cutoff of facilities. The difference between minimize facilities and maximize coverage is the number of facilities to locate (Nozick and Turnquist, 2001). Facilities are located based on distance such that the total weighted cost between demands and solution facilities is reduced between all demand points (Hakimi, 1965). This problem type is traditionally used to locate warehouses (Perl & Daskin, 1985), airports (Min, 1997), and health clinics (Rahman & Smith, 2000).

With the maximize attendance algorithm, facilities are chosen to allocate as much demand weight as possible to facilities, and the demand weight increases in relation to decreasing the distance between the facility and the demand point (Environmental Systems Research Institute [ESRI], 2016). This model enables decision makers to determine the optimal locations of a facility in an area in order to maximize attendance and assist regional demands in the most economical way after examining the geographic distribution of the existing facilities. The terminology “maximize coverage” is used widely in the academic literature as well as by ESRI. There are some important parameters when applying the maximize attendance model, for instance, population density, urbanization, location of existing facilities, and demand of services. Some businesses might benefit from using the maximize attendance model to solve a location problem, for instance locating coffee shops, fitness centers, and medical centers.

The maximize market share algorithm solves the competitive facility location problem. In some academic literature, researchers call it as gravity model. Gravity model concepts are used to determine the proportion of demand allocated to each facility. Market share problem types use a Huff model. This type of model requires more data, e.g., each facility's weight and competitors' facilities. The goal of this model is to catch as much of the total market share as possible with specified the number of facilities. A specific number of facilities are chosen such that the allocated demand is maximized in the presence of competitors (Armstrong & Green, 2007). The total market share is the sum of all demand weight for valid demand points.

The target market share is another location allocation modeling algorithm. In some academic literature, this model refers to it as market share; however, ESRI used the term target market share. This model takes competitors into consideration and tries to select the smallest number of facilities necessary to capture the market share that is specified. The market share problem types are the same as maximize market share in terms of requiring the most data (information and dataset about the facilities and competitors). The maximize attendance problem type and market share problem type can use the same types of facilities. This model chooses the minimum number of facilities needed to capture a certain percentage of the total market share in the presence of competitors (Inderst & Shaffer, 2010).

Modeling Framework for This Study

For this study, the goal is to locate and select AEDs locations within a three-minute cutoff to maximize AED coverage of the city, that is, to have as many demand points as possible located within the service area of AED devices. The three-minute driving time to an AED or local healthcare facility is recommended by the American Heart Association (AHA). Another goal is to maximize this coverage so that travel from the demand points occurs within a specified response time. To simultaneously accomplish these modeling tasks, the maximal coverage algorithm was used, as this algorithm best matched the current modeling needs. It will generate a solution that identifies optimal locations for a finite number of AEDs that would serve as many residents as possible. This algorithm was first introduced by Church and ReVelle (1974). According to Church and ReVelle , the maximize coverage algorithm locates facilities so that as much of the population as possible is covered by the service provided while ensuring that, for those areas that are covered, no one lies outside a pre-defined service distance (p. 103).

An alternative coverage algorithm, the set-covering algorithm, developed earlier by Toregas (1970) was also considered. This algorithm addresses the problem of how to provide coverage to all the demand points within the study area within a specified response time or distance, but using the minimum number of facilities to provide the service. In practice, the maximize coverage algorithm is used when the total cost of covering all demand may be an issue so the goal is to cover as many demand points as possible. The set covering algorithm, on the other hand, is used when all demand points for the service must be covered regardless of cost, but one wishes to minimize the total cost of achieving the coverage (Beneyan et al. 2012). The maximum coverage model was selected as the modeling tool because budget constraints are a factor to be considered. A general model involving maximizing coverage can be specified as follows:

$$\text{Maximize} \qquad z = \sum_{i \in I} a_i y_i$$

$$\text{Subject to} \qquad \sum_{j \in N_i} x_j \geq y_i \quad \text{for all } i \in I \tag{1}$$

$$\sum_{j \in J} x_j = \mathrm{P} \tag{2}$$

$$x_j = (0,1) \quad \text{for all } j \in J \tag{3}$$

$$y_i = (0,1) \quad \text{for all } i \in I \tag{4}$$

where

$$a_i = \textit{population to be served at demand node i}$$

$$y_i = \begin{Bmatrix} 1 \textit{ if the demand site is covered by some facility } j \\ 0 \textit{ if otherwise} \end{Bmatrix}$$

$$x_i = \begin{Bmatrix} 1 \textit{ if a facility is allocated to site } j \\ 0 \textit{ if otherwise} \end{Bmatrix}$$

I = denotes the set of demand nodes

J = denotes the set of facility sites

$$N_i = \{ j \in J \mid d_{ij} \leq S \}$$

d_{ij} = the shortest distance from node i to node j

S = the maximum acceptable travel distance

P = the number of facilities to be located.

In the objective function above, z is the maximized demand coverage predicted by the model. Constraint (1) requires that a facility must be selected before it can be linked to a demand point. Constraint (2) requires that exactly P facilities be located and constraints (3) and (4) are integrity constraints for the decision variables. The maximize coverage location problem is solved using greedy heuristics such as the greedy adding (GA) and the greedy adding with substitution (GAS) heuristics (Church & ReVelle, 1974).

Chapter 3: Materials and Methods

This chapter describes relevant characteristics of the study area and the GIS techniques that were used to estimate optimal locations for the placement of AEDs.

Study Area

The study was conducted in Riyadh, the capital of the Kingdom of Saudi Arabia. Riyadh more correctly transliterates as al-Riyad, which means “the garden” in Arabic. It is located at 24°38′ N, 46°43′ E. The total area of the city is 600 square miles (1,554 km^2) (Menoret, 2014), and the total population is over five million. Approximately 60% of the population is Saudi citizens, while the remaining are foreigners. There are 153 officially-recognized neighborhoods in Riyadh. These neighborhoods were used for census data collection and reporting. There are 165,534 miles (266,402 km) of roads in the city (Teitelbaum, 2009).

The Kingdom of Saudi Arabia is in southwestern Asia. To the west is the Red Sea as well as Sudan. On the eastern border are the United Arab Emirates, Qatar, and Arabian Gulf (Figure 2). Northwards are Kuwait, Jordan and Iraq. It shares a southern border with Yemen and Oman. The Kingdom of Saudi Arabia coordinates are 16^{o} $22^{'}$ $46^{''}$ and 32^{o} $14^{'}$ $00^{''}$ North, and 34^{o} $29^{'}$ $30^{''}$ and 55^{o} $40^{'}$ $00^{''}$ East (Wrampelmeier, 1999).

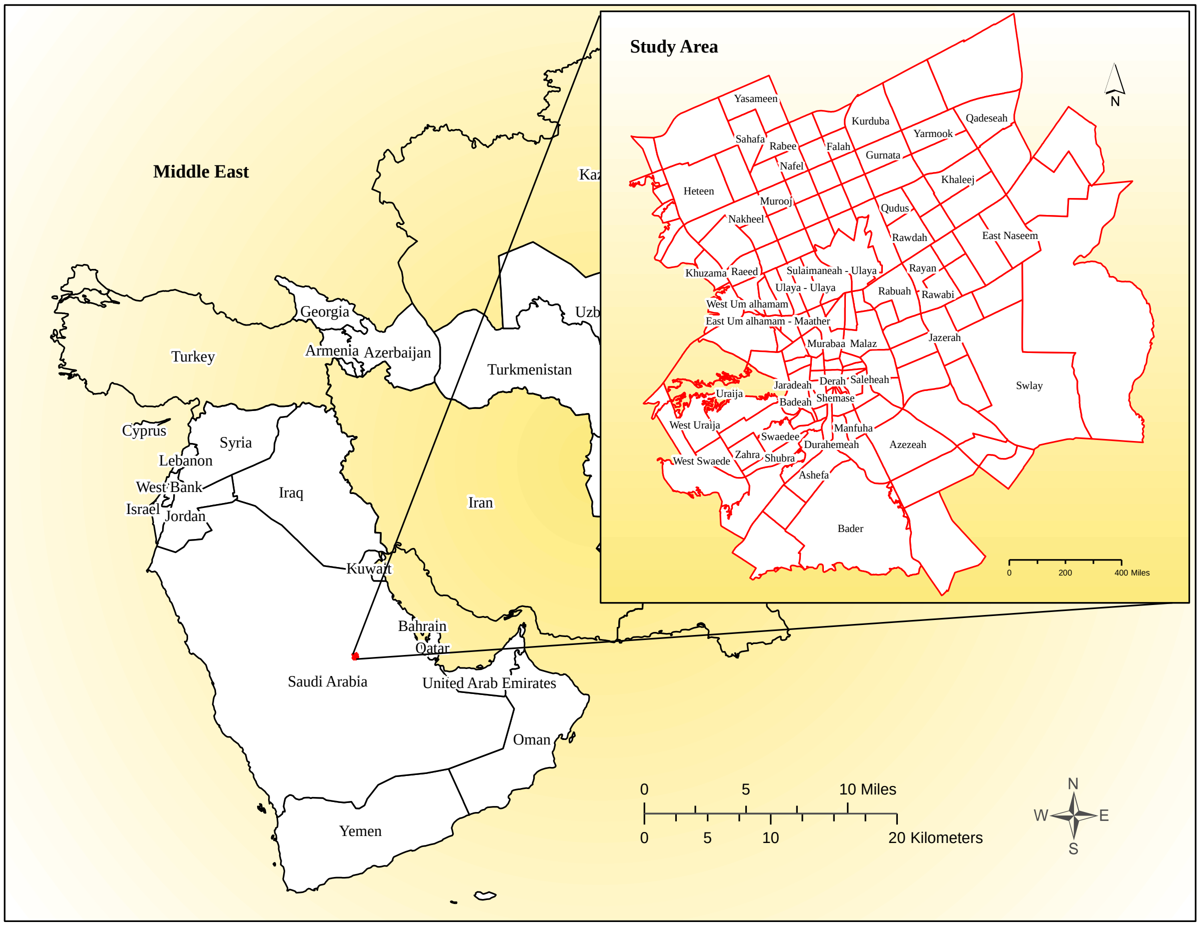

Figure 2. City neighborhoods, Riyadh, Saudi Arabia.

The country is governed by the Al Sa’ud family. Currently, no one is allowed to be president if he or she is not from the Al Saud and the Al al-Sheikh royal family (Wrampelmeier, 1999). Although the need to expand public participation in the political system is recognized, the governing class rejects a Western-style democratic legislative body.

Geographically, Saudi Arabia is a point of convergence for people from around the world because it is home to two of Islam's most holy locales: Mecca and Medina. Pilgrimage is considered one of the most important incomes to the government beside petroleum exports. Yearly, millions of pilgrims travel to Mecca to perform Haj rituals and visit the City of

Medina to perform additional religious rites, including visiting the burial site of Prophet Mohamed (SAW).

A single tier emergency medical service (EMS) serves the city with ambulances alone, responding to emergency calls. Ambulance service is provided by each hospital through the Saudi Red Crescent Society (SRCS); however, private ambulances also operate in the city. The overall mean ambulance response time has been estimated as 13.21 minutes, *SD* = 7.94 min (Alnemer, 2016). This response time is somewhat above the internationally accepted time standard of 8 minutes for cities (Park et al., 2016). Given this mean ambulance response time and the small window of opportunity for defibrillation, rapid access to automatic external defibrillators is crucial for survival from an OHCA attack.

Research Design

To address the research problems effectively, location-allocation analysis was used to model and study the existing time-distance accessibility to public AED devices for different neighborhoods by calculating point- and network-based service areas for pedestrian and automobile travel in addition to study the relationship between AED placements and demand centers accessibility to these AEDs. Alternative AEDs locations were generated using the maximize coverage model under different assumptions. These assumptions allowed for the placement of AEDs at public locations not previously considered, e.g., mosques and schools, and the use of different criteria for travel times to AEDs.

Data Collection

The following datasets were acquired for this study: street network data, census data, city neighborhoods, household census blocks, healthcare facilities, mosques, and schools. These datasets are described below:

Street centerlines. Street network data of Riyadh were downloaded from Trimble Data Marketplace (Trimble, 2016; *https://market.trimbledata.com*). Although street centerlines are available for the entire Riyadh, the dataset does not contain address information that includes building number and street names similar to those found in most western cities.

The street network dataset for Riyadh is classified as “unoriented” with loops (Laurini & Thompson, 1992). Even though the street centerlines may be perfectly fine for drawing maps and for many other purposes, many required fields for network analysis are missing, so the dataset contained what is known as “bad data.” The Advanced Editing toolbar in ArcGIS (Planarize) was used to split street network lines at their intersection. Tiny gaps were fixed by running the Integrate Tool (ArcToolbox – Data Management – Feature Class toolset – Integrate), which add new vertices to the lines.

Census datasets. These were downloaded from the website of the general authority for statistics in Riyadh (https://www.stats.gov.sa/en). The dataset included the following variables: locality (neighborhoods), total population/neighborhood, total male, total female, and Saudi versus non-Saudi (Table 1). The population counts were taken at the nighborhood level.

Table 1

Basic Demographic Data Riyadh, 2014.

Population	**SUM**
Saudi	3,644,778
Non-Saudi	2,086,391
Total Pop	5,731,169

The Geostatistical Wizard offers several types of kriging, which are suitable for different types of data and have different underlying assumptions. The geostatistical method was used to downscale the data to predict the population to census blocks level. Population data for each household block were estimated from city neighborhoods population data. Using the centroids of the census blocks polygons, spline interpolation was performed in ArcGIS to generate a population surface for the entire city. Spline interpolation uses an interpolation method that estimate values using a mathematical functionn that minmized overall surface curvature, resulting in a smooth surface. ArcGIS Geostatistical Analyst tool was then used to compute the mean population for each household block.

City neighborhoods. These are census-based communities within Riyadh. A city neighborhood shapefile was downloaded from the ESRI website (ESRI, 2016; http://www.esri.com/). The shapefile was projected to Ain_el_Abd_UTM_Zone_38N and GCS_Ain_el_Abd_1970 (Mugnier, 2008).

Demand sites (household blocks). City neighborhoods are the lowest level geographic units for census data in Riyadh. However, due to their relatively large geographic size and the lengthy time it would take to traverse one of these units in peak traffic, a decision was made not to use these units as demand sites in the model. Consequently, household blocks or groups of houses that make up small city blocks in Riyadh were used as the demand sites. A household block shapefile for the entire city was downloaded from the High Commission for the Development of Riyadh. In all, it contained 52,217 household blocks. Using areal interpolation, population data from the city neighborhoods were assigned to the household blocks.

Healthcare facilities. Data on healthcare facilities were obtained from the High Commission for the Development of Riyadh. Healthcare facilities (*n* = 304) were subdivided into four groups based on preexisting codes from the Ministry of Health in Riyadh (Table 2): hospital (mustashfa), clinics (eyada), medical care (enya tebya), and primary care facility (markaz sehee). Healthcare facility names were originally written in Arabic and were manually translated to English in a separate column.

A detailed list of the exact location of AEDs in Riyadh was unavailable. Consequently, the location of healthcare facilities were used as proxies for existing AED locations. For sensitivity analysis, the location of mosques and schools were used as facility sites for new AED devices. The healthcare facility dataset were then spatially joined to the household blocks shapefile. Relationships between total population, healthcare locations, and the road transportation network in Riyadh were studied as well. Also, it was used to determine the relative accessibility to AEDs for each neighborhood and the street network.

Table 2

Healthcare Facilities (HCF), Riyadh, 2014

Medical Care	197
Hospitals	47
Primary Care	55
Clinics	5
Total HCF	304

Note. Interpolated from the High Commission for the Development of Riyadh.

Mosques. They are the most important worship places for Muslim nations. Mosques are considered an essential part of Muslim community life. In addition, mosques are usually built in the center of the neighborhood in order to serve the surrounding communities; therefore, they are not only a building for prayer but also a community center. Demographic concentration is one of the factors that the government or a private benefactor decides to build mosques (Masjid). For Friday prayers, special holidays, and yearly in the month of Ramadan, daily mosques attendees are generally very high. In Mecca and Madinah, where Muslims come to perform Hajj and Ummra, the population density can increase to millions of worshipers. In the Kingdom of Saudi Arabia, five times a day at prayer times, all shopping and grocery stores and marketplaces are closed in accordance to the law, until prayer is finished.

Some activities in Islamic family life take place in the mosques, e.g., marriage, newborn celebration (in Arabic it is called Agiga), and prayers for the deceased. The mosque is also a place where Zakat or mandatory charities, alms-giving, are given to those who in need of financial aid and seeking help. Mosques are unique entities in that they are considered by many to be a community of people away from home. In times of need, mosques often take up the costs of funerals through collection or via gift giving. Mosques also help the communities where their congregations are from. Mosques have become involved in many different aspects of public causes (Cesari, 2005). Since the mosques are an essential part in the city and are most of the time built in the center of neighborhoods as well as they are open through the year, for these reasons, and because of large gatherings in these places, mosques are very important potential locations for AEDs.

The attribute tables of the mosques shapefile contain the mosque name in Arabic, the parcel ID, year of establishment, etc. Mosques (*n* = 1371) were used as alternative demand points to expand the AEDs coverage when running the location-allocation model. The blocks of households were used as a demand points, even though the cost for allocating AEDs to the large number of household blocks would be reasonable.

Schools. The schools dataset was downloaded in the form of a shapefile from the High Commission for the Development of Riyadh. The attribute table consists of 2,443 schools subdivided into: preschool, kindergarten, primary, secondary, and universities. Also, the attribute tables contained the name of the institute, school type (male or female), school code, number of grades, number of floors, and number of Saudi and non-Saudi students. Community colleges and universities (*n* = 34) were used as potential locations for deployed AEDs. Faculty members and staff as well as young adult students in colleges and universities will be easy to teach to learn how to operate the AED machine compared to younger children. In addition, mature students might better understand the nature of OHCA. For the above reasons, colleges and universities were selected to participate in the study as a candidate location to deploy new AEDs.

Each attribute table in the database includes geographic location of the feature mentioned above. The geographic locations of healthcare facilities (HCF), mosques, and schools were used to determine potential sites for deploying the AEDs, using the maximize coverage model.

Data Processing

Microsoft Excel was used to organize household block-based demographic data and other census information. The ArcGIS attribute join function was used to join the Excel tables to the 52,217 blocks polygons. An ArcGIS spatial join was performed to determine the number of healthcare facilities contained in each household blocks. This process involved overlaying the census blocks map on the healthcare points map and then matching each point to a block based on the correspondence between the coordinates of the point and the polygon that encloses the point. Spatial join creates a field in the block layer attribute table that contains a count of the number of the different features per block. Both the point data and the polygons were used to assess the degree of clustering of healthcare facilities in Riyadh.

Data Analysis

Several GIS techniques were employed to analyze the dataset and to answer the research questions. First, choropleth thematic mapping was used to understand the distribution of population within Riyadh and the distribution of healthcare facilities, which in this study, are proxies for current AED locations.

ArcGIS Hot spot analysis tool (Getis-Ord Gi* statistic) was used to study the spatial pattern of AEDs in the study area and the spatial pattern of demand points. The importance of this analysis is that it identified the degree of clustering of healthcare facilities and population in Riyadh. Knowledge of the degree of clustering of demand and supply points can be used in decisions regarding the placement of new AEDs. For example, if a community already has a large number of healthcare facilities in close proximity to each other, then such a community would not be a high priority for new AED placement. On the other hand, if a community has a large, highly clustered population, but few AEDs, then such a community could be a target for additional AEDs.

To check for spatial inequity in the siting of facilities, the spatial distribution of population in Riyadh was compared with the distribution of health facilities using choropleth maps and cluster maps produced by ArcGIS Getis-Ord Gi* Statistic tool (Getis & Ord, 1992).

Travel Time Analysis

The ArcGIS Network Analyst extension was used to compute travel time along the road network. Travel time is used in location-allocation modeling to compute the least time route along the network between demand points (p) and supply centers. Two types of travel time were computed: vehicle travel time and pedestrian walk times to healthcare facilities.

Vehicle travel times. To prepare the street network data for drive time analysis, the streets segment lengths were converted to miles (1 mile =1,609.34 meters) and minutes to hours. A column was added to the street network attribute table to calculate the time according to the following formula:

Minutes = [SHAPE_Length] / 1609.34 * 60 / [speed]

A three-minute driving time to an AED or local healthcare facility is recommended by the American Heart Association (AHA) as an appropriate for out-of-hospital cardiac arrest. Death can occurs within minutes if the OHCA victim does not receive treatment. The OHCA victims' chance of survival decrease by 7 to 10% for every minute that poses without defibrillation (AHA, 2000). In order to realistically model distance covered by a three-minute travel time in Riyadh, it is necessary to take the traffic volume into consideration. In the absence of traffic volume information, estimates were developed on the average speed on different road types given traffic flows during peak hours. The estimates were developed from observed during field work in Riyadh and from consultations with people familiar with the city. Table 3 shows the estimates that were developed and used during the location-allocation modeling.

Table 3

Average Speeds for Each Main Road

Road type	Average speed (mph)
Residential street	3 – 12
Tertiary link	60
Bus guideway	12
Road under construction	12 – 40
Motorway	70
Motorway link	40 – 60
Path	50
Primary link	50

Note. Interpolated from the street's shapefile (High Commission for the Development of Riyadh).

Pedestrian travel time. A pedestrian is defined as a person walking along a road or in a developed area. In general, the average walking speed for older pedestrians was 4.11 feet per second. For the younger people, the average is 4.95 feet per second; for older males it is 4.31 feet per second, and for older females it is 3.89 feet per second (Knoblauch, Pietrucha, & Nitzburg, 1996). Pedestrian walking time service areas were delineated in order to determine distance criteria for accessibility to AEDs in the location-allocation model. Pedestrian walking times to AEDs were calculated using Network Analyst and the street network. Two columns were created in the street network's attributes table. The first column was used to store the street segments length measure in feet. The second contained the average speed of pedestrians. Assuming a pedestrian can walk at 4.11 feet/second, walk time in minutes would be 246.6 feet/min and it would be 0.046704545 mile/min (1 mile = 5,280 foot). This speed was multiplied by 2 keeping in mind that people will likely jog through an urgent condition (Kwon, Lee, Yu, Huh, 2016). Therefore, the speed was calculated using the following formula:

0.046704545 mile/min (speed) X 2 = 0.09340909 mile/min

Since people are allowed to walk in the direction they pick, one-way restriction was neglected in the analysis.

Location-Allocation Modeling

Location-allocation modeling as implemented by ArcGIS 10.5 was used in this study to arrive at optimal locations for the placement of AEDs. The ArcGIS location-allocation tool is able to handle seven different problem types, i.e., minimize impedance, maximize coverage, maximize capacitated coverage, minimize facilities, maximize attendance, maximize market share, and target market share. These models were summarized in the literature review. Modeling was based on the premise that people tend to use AEDs that are closest to them rather than ones that are farther away. The maximize coverage model was applied in order to generate different coverage scenarios.

To implement maximize coverage model in ArcGIS, the following datasets are needed: (a) demand points, (b) potential additional AED locations, and (c) location of known healthcare facilities, which are proxies for existing AEDs. These datasets are discussed in details below.

Demand points. Initially, city neighborhoods were considered as demand points; however, these proved to be too large to serve as allocation points. Not only did they represent geographically large areas, but their population sizes were also too large. The average population for the neighborhoods was 37,458. Since the allocation of a single facility to large, densely populated areas seemed counterproductive, smaller-sized communities were sought. One option was to use blocks of households similar to the concept of census blocks in the US. This option does have merit in that it would avoid many of the issues involved in using drive time analysis without the needed traffic data as a means of allocating AEDs.

Block based community population was estimated using areal interpolation, a function available in the geostatistical analyst tool in ArcGIS 10.5. The average population for the block-based communities was 4,180 compared to 37,458 for the city neighborhoods. The 52,217 census blocks centroids were loaded into the location-allocation model as "Demand Points" layer.

Healthcare facilities. Healthcare units in the city were used as proxies for AEDs points, as these were the most likely places to find AEDs. The healthcare facilities were stored as vector points. The layer was loaded into the location-allocation model as the “Facilities” layer.

Weights. Riyadh is served primarily by healthcare facilities of different ranks, medical care, hospitals, primary care units, and clinics (Table 4). Since these facilities provide different levels of services and may be associated with varying numbers of AEDs depending on their category, a weight was assigned to the different types of facilities, to account for the varying numbers of AEDs that may be found at their facility.

Table 4

Healthcare Facility Classification in the Study Area

Healthcare Facility	Hospitals	Medical Care	Primary Care	Clinics
Number	47	197	55	5
Weighted point	25	15	10	5

Note. Interpolated from the High Commission for the Development of Riyadh.

The presence of one or more healthcare facilities in census block-based communities will affect the number of new AEDs allocated to that community. Consequently, it was necessary to attach weight to the census block communities to reflect their need for additional AEDs. The weight that was applied was based on the number of existing healthcare facilities in a community and the population size of the community (Algharib, 2011).

Running the ArcGIS location-allocation model. To run the location-allocation model, the required data were loaded into the software and several location-allocation properties were set. These properties included the direction of travel between facilities and demand points; when calculating the network costs, the cost attribute to be used as impedance in the analysis, and the problem type to be solved. The number of facilities that the solver should locate includes the following: impedance cutoff, impedance transformation, and impedance parameter.

One of the research goals was to provide coverage to as many people as possible, with the constraint that accessibility to the AEDs must be within three minutes travel time for anyone who is covered. With this goal, then the maximize coverage is the model to use, as any demand point selected would be within three minutes of an AED. Maximize coverage model was used to analyze the current AEDs locations. This model was tested in order to find the best AEDs coverage and maximum community served. The models were used to solve an AED-expansion scenario, which started with the existing location of healthcare facilities then expanded to include AEDs located in mosques and schools.

Chapter 4: Results

Exploratory Spatial Data Analysis (ESDA)

Thematic mapping. Figure 3 shows the distribution of population in Riyadh by census blocks based on 2014 census data. The choropleth map also shows the number of healthcare facilities by neighborhood. It is very obvious that the population distribution is spatially uneven with the highest densities encountered farther away from the city center. The downtown area, which is 17.5 square mile, consists of mostly of government offices, open space, and commercial facilities.

When the healthcare facilities points were overlaid on the thematic map, the data showed some amount of spatial mismatch between population distribution and the location of healthcare facilities. Most of the existing healthcare facilities were located in the central parts of Riyadh in tracts that had low to moderate levels of population density (Figure 3). Large areas on the periphery of the city with moderate to high levels of population density were not covered by healthcare facilities and their associated AEDs. Evidently, Riyadh is currently not appropriately covered with AEDs.

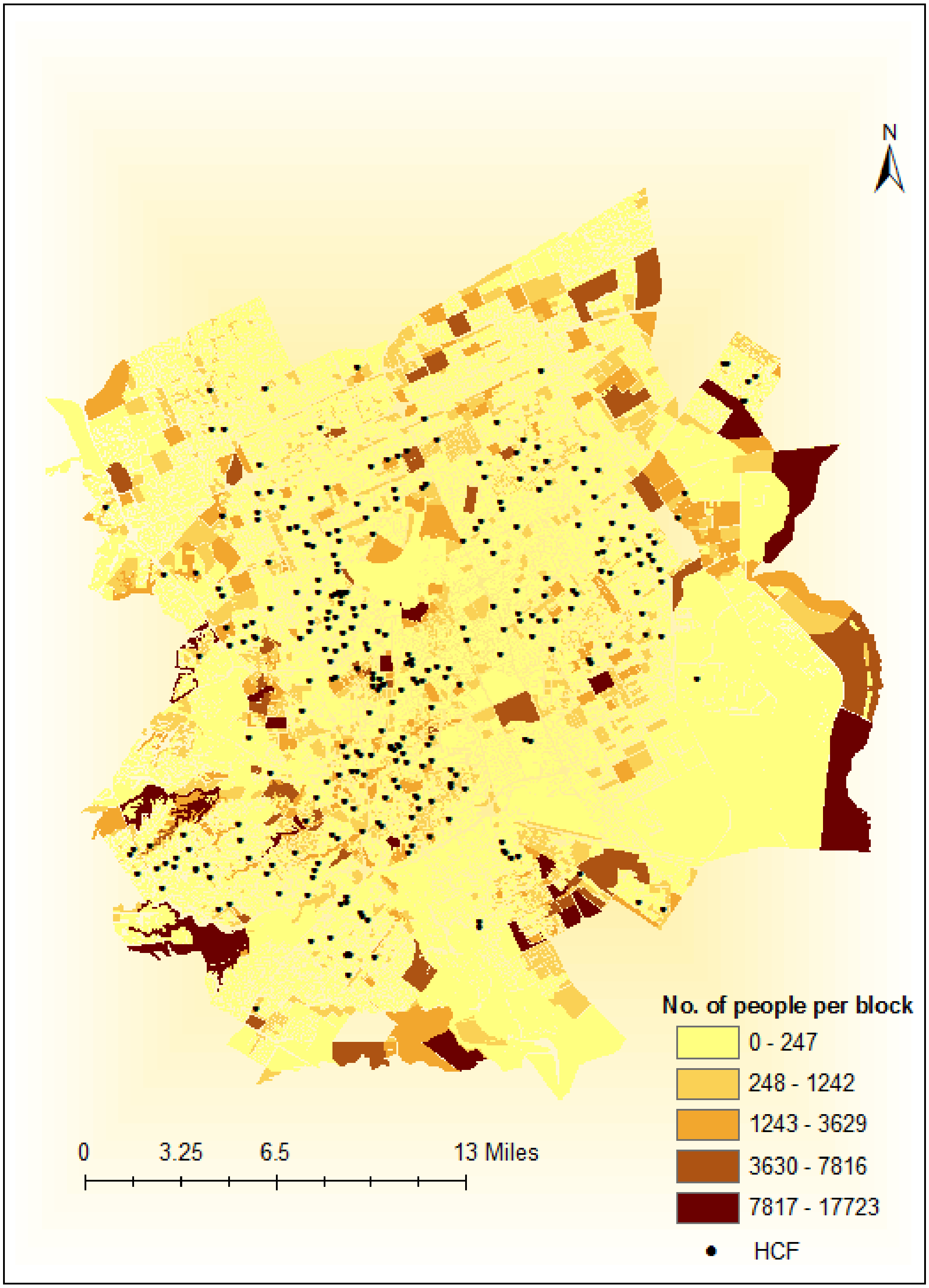

Figure 3. Riyadh's Population density by census blocks, 2014.

Cluster analysis. The cluster analysis revealed a large area of population cluster in the north and north-eastern part of the study area and a large cold spot or contiguous area of low population density on the east side of the city (Figure 4). There was also a large contiguous area of low population density on the east side of the city. The cluster analysis also revealed three clusters of healthcare facilities, one large one in the northeast and two smaller ones in the south (Figure 5). Evidently, the clusters of healthcare facilities do not spatially coincide with population clusters, an observation that substantiates the thematic mapping.

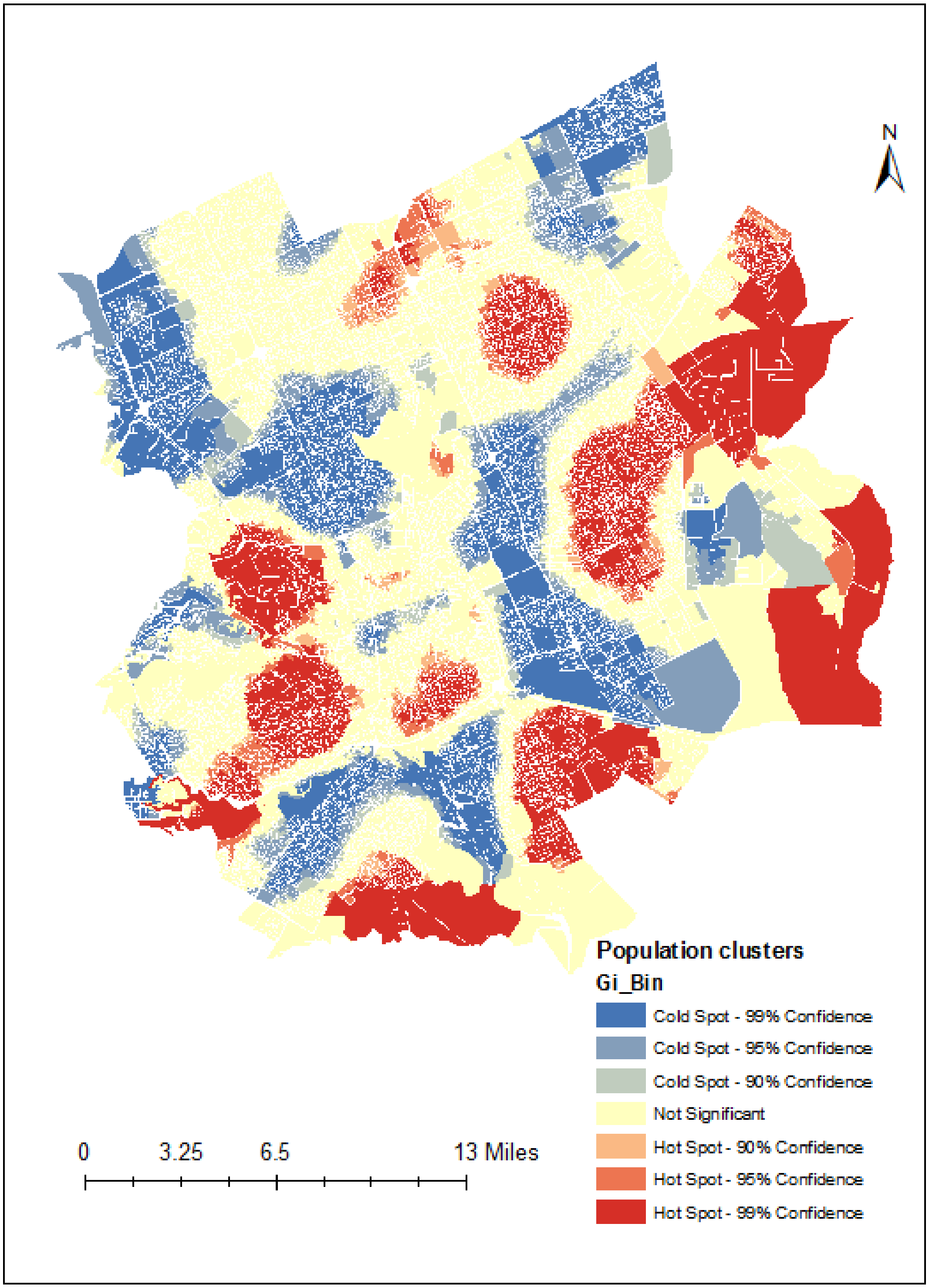

Figure 4. Population clusters in Riyadh.

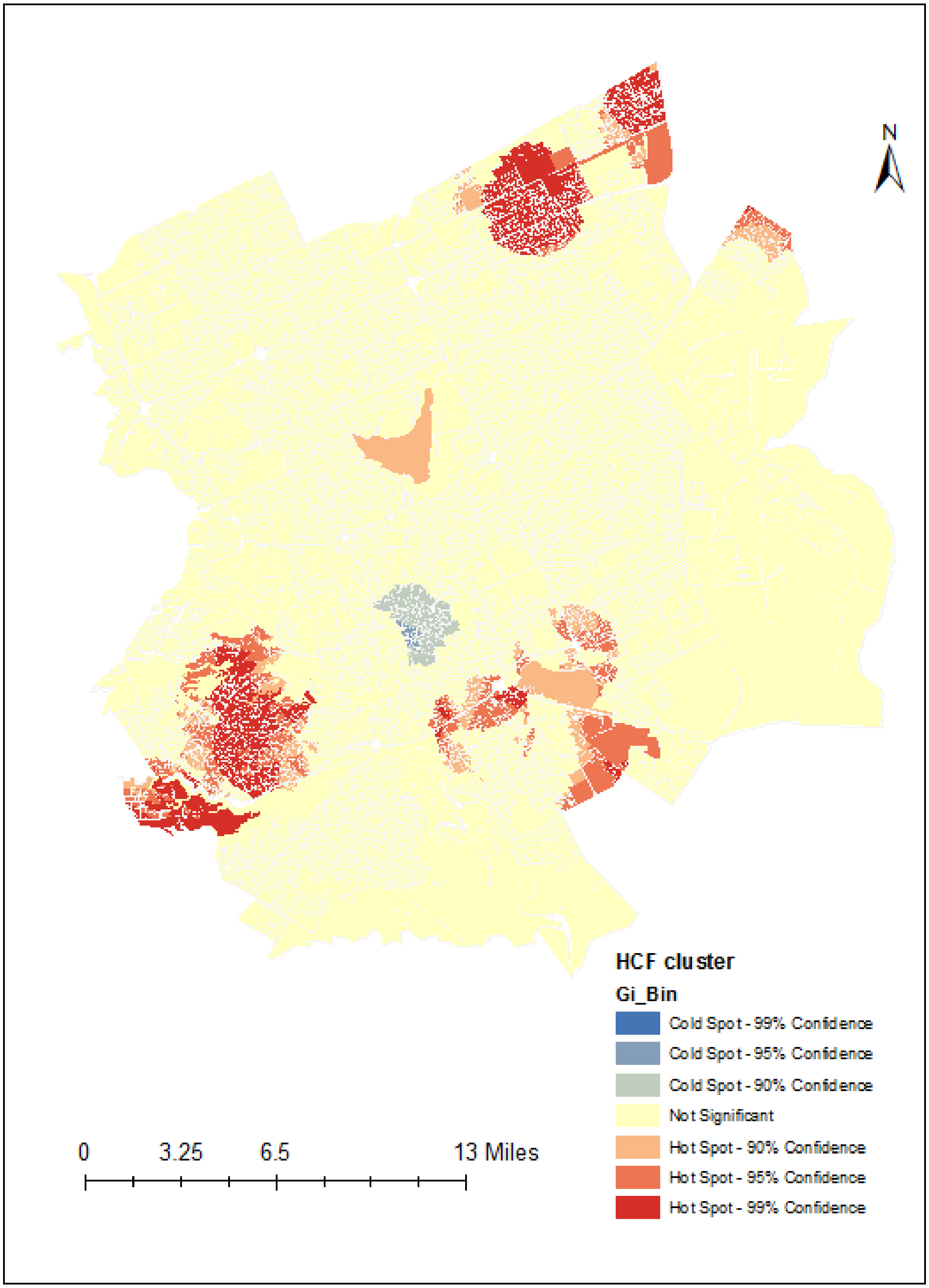

Figure 5. Healthcare facility clusters in Riyadh.

Network Analysis

Travel time analysis (closest facility). The current level of accessibility to hospitals and other healthcare facilities (HCFs) for OHCA patients in Riyadh was assessed using network analysis. The existing road network was used to model and calculate vehicle travel times between OHCA victims' locations and healthcare facilities (AEDs locations). The analysis was done to obtain average distance and travel time from OHCA victim's locations to the nearest hospital or healthcare facilities.

Figure 6 display the results of the accessibility analysis. The figure shows drive time accessibility and the coverage area using three-minute cutoff time as recommended by the AHA. Even when demand constraints are not accounted for, the result shows that all sections of the city are not within three minutes of healthcare centers. In other words, even though the HCFs were accessible through road network, the percentage of household block coverage was low.

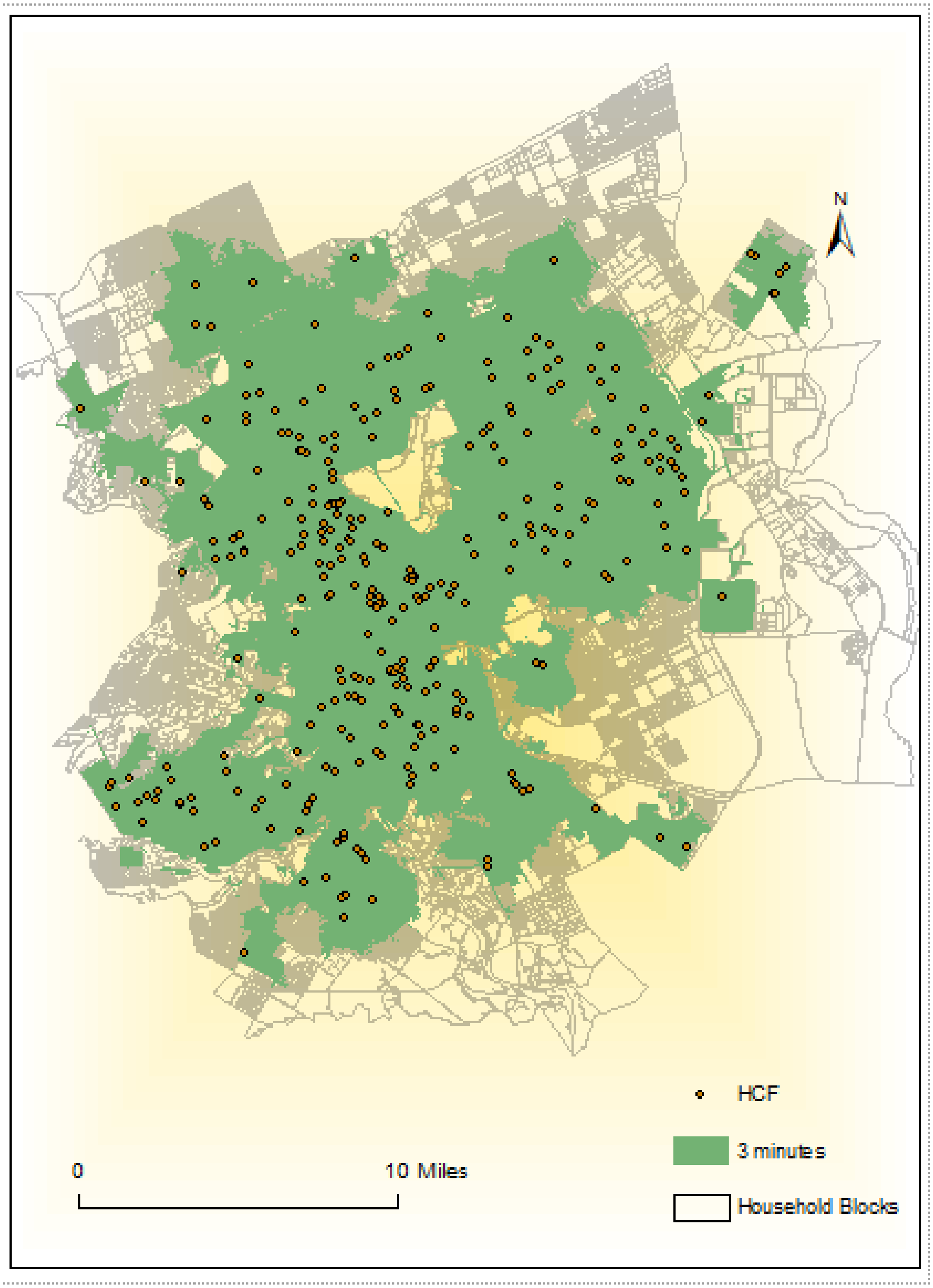

Figure 6. Healthcare facility service area coverage to household blocks within three minutes driving.

Pedestrian travel time. Figure 7 displays the pedestrian travel time results of the accessibility to HCFs (*n* = 304) in the study area. The pedestrian services time assumes all HCFs have AEDs and are opened for services 24 hours every day. The figure shows pedestrians' time accessibility to HCFs in three minutes of walking. It is obvious from the map that a 3-minute walking distance from healthcare facilities does not allow coverage for a significant proportion of the city. As mentioned in travel time analysis section, this method also does not give how many people have been served in the city.

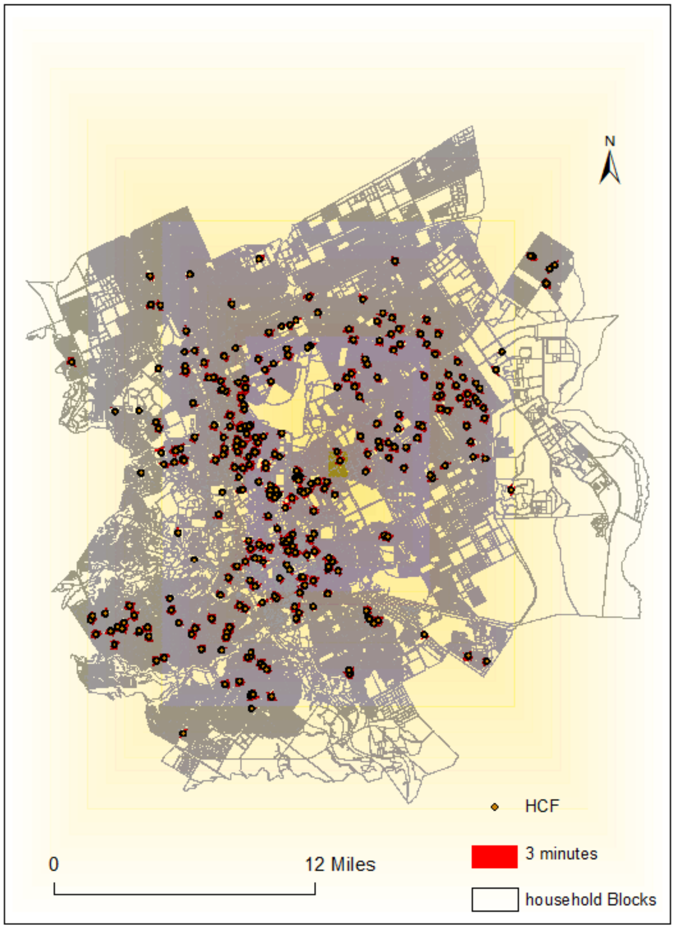

Figure 7. Time-based healthcare facilities service area coverage scenarios (Pedestrian).

Location-allocation model. This section reports the results of the maximize coverage modeling using the existing healthcare facilities and blocks-based communities. Results are reported vehicle and pedestrian access to AED devices. In addition, model results with additional supply facilities, mosques and school are reported.

Existing AED supply and demand with population as weights and vehicle traffic as the distance element. When the maximize coverage model (Figure 8) was run using the existing AEDs and census blocks centroids as a demand supply with their weighted population and driving time (minutes) as distance element, only 39,004 of the 52,217 demand points were allocated to the chosen facilities. The remaining points were farther than the three-minute cutoff. The model output showed that 292 AEDs were used to cover the 39,004 neighborhoods. Evidently, this represents an underutilization of AED resources, as 12 of them were not being effectively utilized. Furthermore, this was occurring within a context where 74.7% of household blocks or 3,835.166 people being served (Table 5). Clearly a better spatial arrangement is desirable.

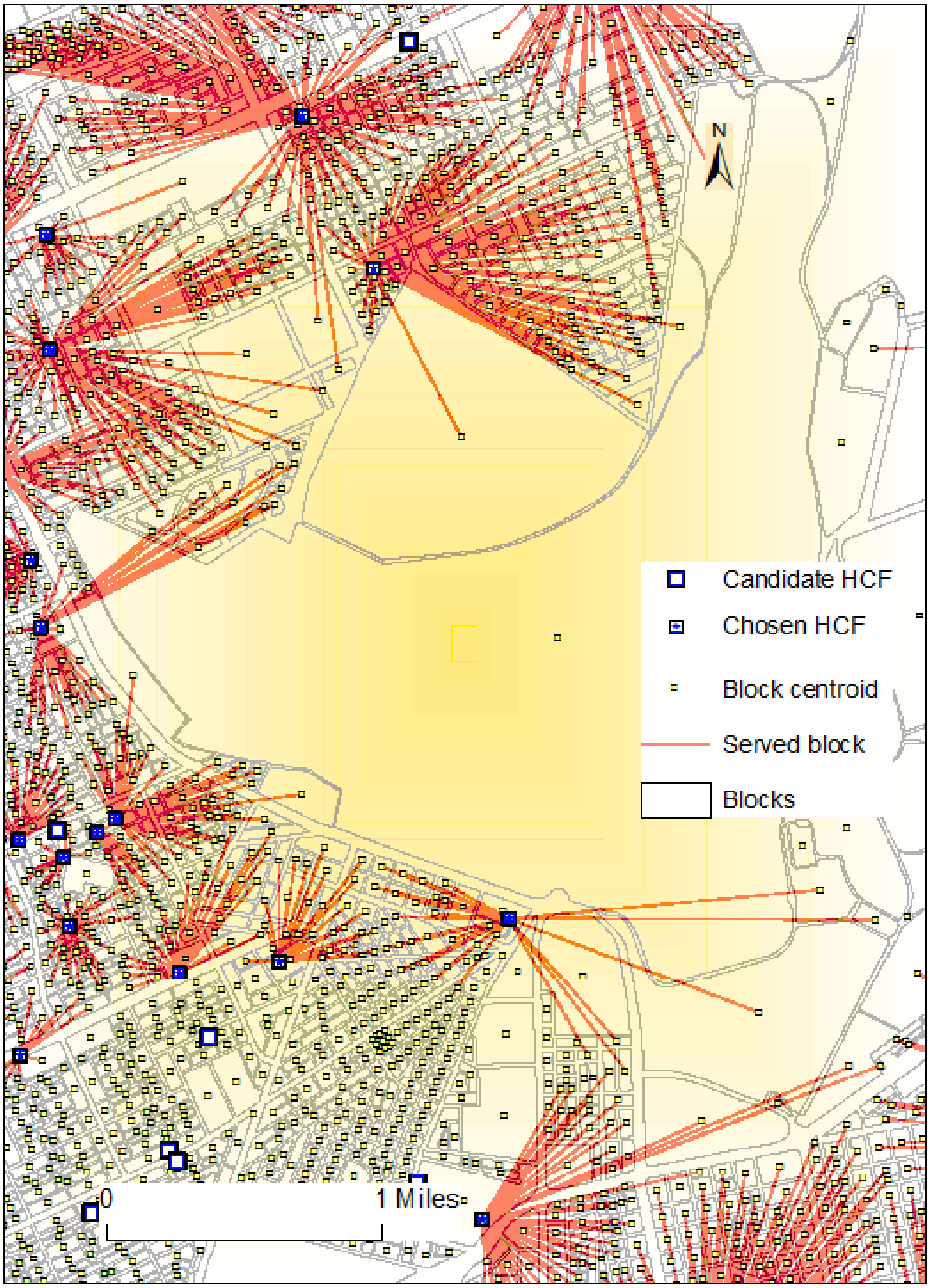

Figure 8. Existing AEDs coverage in relation to population (vehicle).

Model results with additional supply facilities based on population weights and vehicle travel. After adding the additional 1,371 mosques to the model along with the original total number of the facilities, the location-allocation model showed significant improvement. Of the 52,217 demand points, 43,391 were allocated to the chosen facilities. This allowed a total of 4,272.229 of the population to be served. Evidently, there are benefits to using mosques and as places to deploy new AED devices to increase coverage. The percentage of household blocks served increased to 83.1 (Table 5). Clearly, this represented a significant improvement. Further improvements in coverage could be achieved by adding additional AEDs in places such as schools.

To add additional facilities to the study area and to simultaneously solve for optimality, the 34 educational facilities were loaded into the location-allocation model, and maximize coverage model was rerun. The result showed no improvement in terms of the percentage of served blocks as well as the served population (Table 5).

Table 5

Maximize Coverage Model Summary

		No. of facilities	Chosen	Candidate	Unserved population	Served population	Served population (%)	Unserved blocks	Served blocks	Served blocks (%)
Vehicle	HCF (existing situation)	-	292	12	718,169	3,835,166	84.2	13,213	39,004	74.7
	HCF and Mosques	1,675	1,341	30	281,106	4,272,229	93.8	8,826	43,391	83.1
	HCF, Mosques, and school	1,709	1,370	35	281,070	4,272,265	93.8	8,825	43,392	83.1
Pedestrian	HCF (existing situation)		267	37	4,157,908	395,427	8.7	47,319	4,898	9.4
	HCF and Mosques	1,675	1,351	20	2,853,129	1,700,206	37.3	29,571	22,646	43.4
	HCF, Mosques, and school	1,709	1,381	24	2,840,819	1,712,516	37.6	29,420	22,797	43.7

Existing AED demand supply and demand with population as weights and pedestrian traffic as the distance element. The maximize coverage model (Figure 9) was ran using the existing AEDs and census blocks centroids as a demand supply with their weighted population and pedestrians time (minutes) as distance element.

Out of the 52,217 demand points, only 4,898 or 9.38% were allocated to the chosen facilities. The number of people likely to be served under this model scenario was 395,427 or 8.7% of the population. This situation represents a very low coverage rate as well as an underutilization of resources on the part of the AEDs, as 37 of them were not selected by the model.

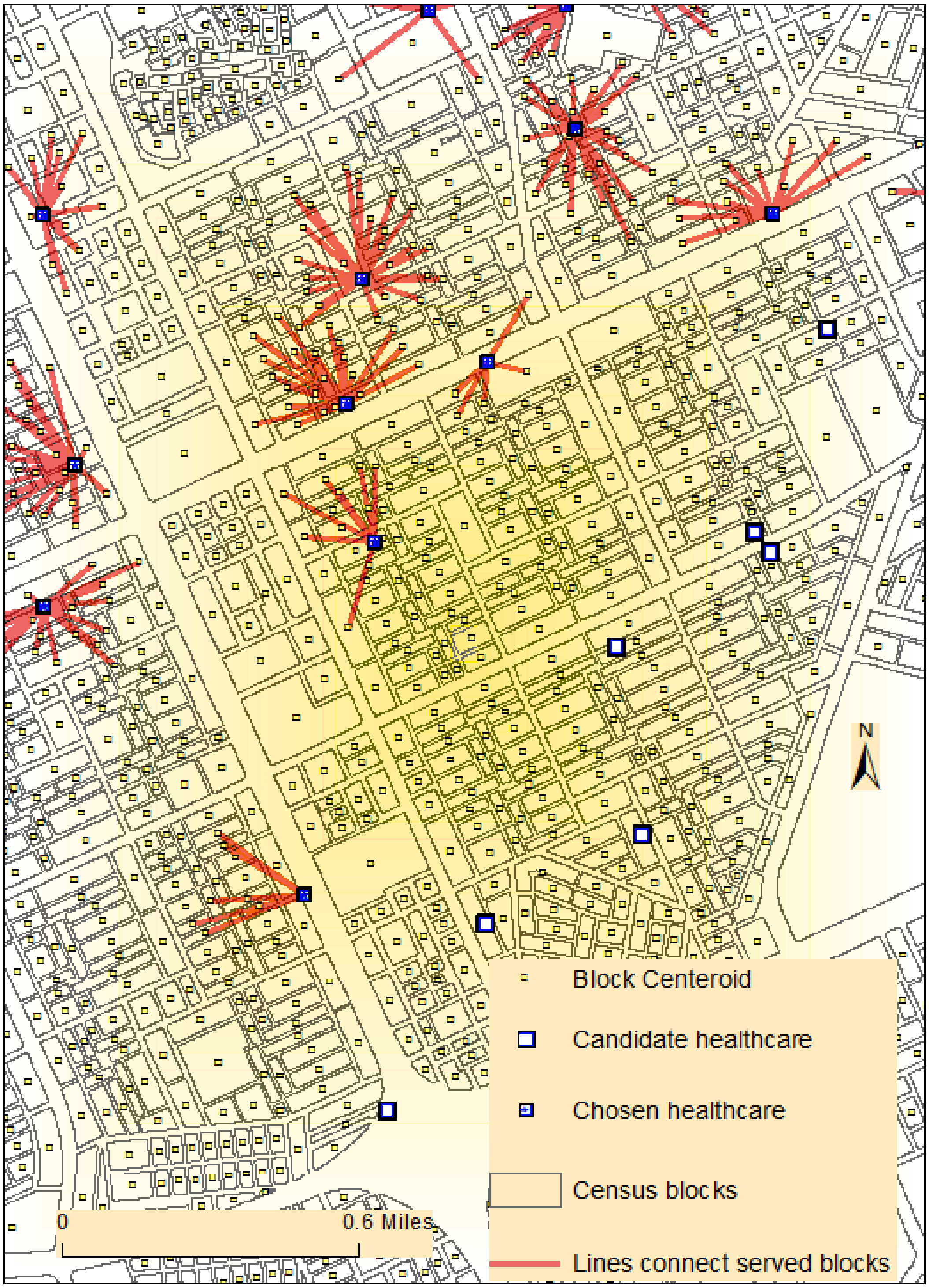

Figure 9. Existing AEDs coverage in relation to population (pedestrian).

Model results with additional supply facilities based on population weights and pedestrian travel. When the model was rerun with the addition of mosques as AEDs supply points and three-minute cutoff point, the number of household-blocks covered increased to 22,646 or 43.4%. The number of people that are likely to serve by the assigned AED was 1,700,206 (37.3%).

When the schools were added to the model, the percentage of served blocks and percentage of served population were increased by 0.3%. In other words, the small number of schools made no appreciable difference to AED coverage.

Chapter 5: Discussion of Results

As expected, the model results indicated much better household block coverage for vehicular access to AEDs (75%) than pedestrian accessibility (9%) when using the existing location for the HCFs. These percentages were increased to 83% and 43% when the model was re-run using mosques location as a part of the solution, for vehicular traffic and pedestrian, respectively. There was no considerable increase in AEDs coverage when the schools locations were added to the model beside the mosques and existing HCFs. The coverage percentages were 83% and 43% for vehicular and pedestrian, respectively.

With vehicular traffic, greater distances can be covered quickly; hence, most household blocks are within the three-minute cutoff point from existing supply sites. However, these results assume that private vehicles will always be immediately available to transport patients to AED sites and that the traffic situation will always permit the three-minute level of accessibility. Since neither of the two assumptions is particularly reliable, these results raise the important policy question as to whether the AED placement system should be designed to cater, in the first instance, for pedestrian accessibility (Kwon et al., 2017) and then secondly for vehicular access.

This research advocates that given the high traffic volume in Riyadh, reliance on vehicular traffic should not be the first priority in modeling access to automatic external defibrillators. Rather, the emphasis should be on expanding pedestrian access to automatic external defibrillators since the issue of dealing with high traffic volume would be significantly reduced.

Although the model results indicated a household block coverage of 43% with the combination of healthcare facilities, mosques, and schools, for pedestrian traffic, it should be noted that household block coverage increased much more for pedestrian accessibility compared to vehicular accessibility when mosques were added as potential AED sites, i.e., from 9.4% to 43% coverage compared to 75% to 83%. For continued expansion in household block coverage for pedestrian coverage, it will be necessary to locate AED devices in a broader range of public facilities, not just schools and mosques to make them more accessible to pedestrians. Such facilities include police stations, shopping areas, primary and secondary schools that are within walking distance of household blocks. This will increase the survivability of OHCA. The Ministry of Health in Saudi Arabia should enact laws and/or regulations requiring that public gathering places should have AEDs in walking distance. These include, but are not limited to, health clubs, schools, airports, malls, and sports arenas.

Notwithstanding the emphasis on strengthening AED accessibility for pedestrian traffic, expanding access to defibrillators via vehicular traffic is also important if only because this may often be the only feasible option for accessing AED services in many cases. However, the expansion strategy is different from that of pedestrian accessibility. With vehicular traffic, it appears that increasing the number of potential AED supply points within the existing pattern of geographic clustering of population in the city does not expand household block access to defibrillators. This is evidenced by the fact that an additional 1,405 new potential AED sites only expanded household block coverage from 75% to 83%. Given the spatial clustering of the population, it is unlikely that adding new facilities to clustered areas will increase coverage. On the contrary, a higher level of coverage can be achieved by identifying additional public facilities in low density peripheral areas of the city where supply sites are minimal.

In general, based on the model results, the overall strategy to improve AED accessibility in the study area is to identify more potential sites for AED placement in the densely populated sections of the city to improve household block access for pedestrian traffic. At the same time, there is a need to identify more potential sites for AED placement in lightly populated, peripheral areas of the city to improve household block access for vehicular traffic.

On a different note, one of the weaknesses of this study is that only a narrow range of public facilities was taken into consideration as potential sites for locating AEDs, i.e., healthcare facilities, mosques, and schools. However, the model is very flexible and depending on resource availability, a broader list of public facilities can be generated and easily incorporated into the analytical framework. Other public facilities that can be easily incorporated into the model include shopping malls, sports stadiums, other places of entertainment, hotels/motels, central bus terminals, government offices, restaurants, and industrial/manufacturing plants.

One strength of the study is that the location allocation algorithm used to guide the placement of AEDs is not data hungry, and the results can be used to plan better access to AEDs in the study area. As demonstrated in this research, by using the location-allocation tools in ArcGIS Network Analyst and readily available datasets, it is possible to use well-established modeling frameworks to guide the placement of AEDs. In the past, such modeling capability would have been outside the reach of most agencies. However, with the advancement of computer technology and access to spatial data, public health analysts familiar with GIS can use the methods described in this analysis to select suitable locations for placing AEDs in local public facilities.

Optimized deployment of AEDs can provide broad-based coverage to a large number of people in Riyadh and could save lives and associated costs. In the UAE, installing defibrillators in a public places decreased the OHCA mortality rate from 90% to 30% (Ong et al., 2015). In Saudi Arabia, similar results can be achieved if a broad-based AED placement program is implemented.

In this study, a city-wide top down approach to AED placement was described that centralized Ministry of Health officials could easily replicate without much consultations with local officials. This approach can lead to placement of AED devices at locations that could minimize their usage due to ordinary people's lack of knowledge about where these AEDs are located and also how to use the devices. To better meet the needs of local user communities, a community-based AED placement model may be appropriate. Such an approach would actively involve local community officials in the identification of possible local public places, e.g., schools, mosques, community centers, police stations, health centers, etc., that would best serve as AED supply points. The location allocation technique would then select those AEDs that maximize coverage. Involving local community leaders in the project may also guarantee higher usage rates as well as security and maintenance of the devices.

One methodological issue with location-allocation modeling is that it does not recommend the initial location of supply points, as in a typical GIS site selection analysis. It only selects p optimal supply points from a list of n located candidate points where $p < n$. This being the case, researchers have to ensure beforehand that spatially equitable distributions of points are proposed. To some extent, this was done in this study; however, if the necessary spatial analysis is not done during the initial stages of a location-allocation project, it could perpetuate spatial inequities in the model results.

Finally, it is important to point out that identifying schools and mosques for the possible placement of AEDs is only one part of any project aimed at providing fast access to AED by members of the public. Other aspects to such a project may include issues relating to determining where exactly in the school or mosque should the AED be located, accessing the device when the facility is not opened for regular business, improving awareness of the devices by members of the local communities, training members of the public to use the devices, improving the likelihood that bystanders would actually use the devices if there is an OHCA event, and maintaining the AEDs. While these are important issues, they are outside the scope of this analysis.

Chapter 6: Conclusion and Recommendations

Geographic information systems (GIS) can be used with sophisticated mathematical models to produce maps that highlight communities and neighborhoods that are in need of automated external defibrillators (AEDs). AEDs continue to be of extreme importance in the OHCA survivability and healthcare industry. Many individuals do not know the usefulness of AEDs, and therefore, developing awareness of this device is essential. It is known that defibrillators improve resuscitation in the minutes after sudden cardiac arrest; therefore, there should be improved efforts and accessibility of this defibrillator equipment. At present, although insight into instrument and conditions of sudden cardiac death is increasing, the methods described in this study for identifying the best location to deploy AEDs in Riyadh could increase survival rates.

Using GIS to optimally place AEDs is far better than "just eyeballing" locations. This dissertation used the actual street data of Riyadh, the location of demand for AED devices, and the maximum travel time to OHCA devices to model optimal locational for AEDs. With proper configuration of the ESRI Network Analyst extension, the model can be efficiently run within ArcGIS to suggest an optimal location to deploy new AEDs.

Several important perspectives emerge from this research. Firstly, the current low level of AEDs in Riyadh is of concern and must be reevaluated because large segments of the city are not within required access to AEDs. Research on the location of AEDs in the study area has been almost lacking. This may be a result of relative ignorance about the disease by residents within the community. Secondly, the various GIS methods used in this research for evaluating the AEDs locations are convenient and the results can be used to improve the healthcare services in the study area and elsewhere in the Middle East.

Public-access defibrillation programs require strategic placement of defibrillators so that places where the risk of cardiac arrest is high should have greater access to the devices compared to places where the risk is low. In this research, location-allocation models were demonstrated. As implemented in a GIS software such as ArcGIS, it represents a powerful, yet easy to implement tool to guide the strategic placement of AEDs. Moreover, the tools and modeling framework are sufficiently flexible to allow new datasets to be easily incorporated into sensitivity analysis. The methods described in this research can be used in other cities in the Middle East to guide the placement of AEDs.

Maximize coverage modeling is a mathematical approach for deploying new AEDs. However, its usefulness can be enhanced if analytical techniques such as cluster analysis can be used before applying the maximize coverage model to identify general priority areas. Such areas may include places where older people live. With better localized demographic data and knowing where the high risk of OHCA victims are, greater benefits can be achieved from location allocation modeling.

In the literature, CPR is usually recommended as a first step before AED. Bystander participation is crucial for the improvement of survivability. If bystanders have CPR knowledge that should be the first step in the chain of survival and the next step in this process is EMS arrival or AED. The use of AEDs and perhaps training for CPR might be enhanced by having AEDs in schools and student training on how to use the AED and perform CPR. This could be part of the curriculum so that students know the location of AEDs and how to use them. Religion may be an issue in performing CPR or using AEDs in a city like Riyadh. Some people may be reprimanded for performing CPR to a collapsed person of the opposite gender. There is also fear of reprisal of certain laws in Saudi Arabia relating to harming another person. CPR can be construed as doing harm as it is compressing the chest.

This study highly recommends a direct phone line to ambulance and police services to be placed next to AEDs machines. In addition, a smart phone application can be developed to enable people to quickly locate the AED devices that are closest to them. There is even the possibility that drones can be developed to quickly deliver AEDs to patients.

As mentioned earlier, the conceptual framework of this study has applicability to other countries in the Middle East. However, the data for a certain area should be compatible with ArcGIS. Some of this data includes, but is not limited to, a well-defined street network, demographic dataset, and OHCA dataset.

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