Planning and location of health care services in Jeddah City, Saudi Arabia: Discussion of the constructive use of geographical information systems

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Abstract

Geographical information systems (GIS) is used for health care planning due to the increasing availability of geo-coded health data that is moving the field towards to health information systems. The aim of this paper is to present GIS applications for planning health services in Jeddah City. The discussion is focused on three major issues: i) identifying the location of health service facilities and their distribution; ii) modelling the level of density needed for health service facilities; and iii) identifying the required levels of accessibility to these health services. The issues covered include GIS, choropleth mapping, kernel density modelling, Euclidean (straight-line) distance and drive-time distance models. These approaches are essential and considered the major spatial decision models required to support health care for decision-makers and planners in Jeddah City, Saudi Arabia.

Introduction

Geographic information systems (GIS), used for the integration and analysis of geographic data in a computerized environment, based on spatial data that result from observation and measurement of phenomena referenced to their locations on the earth's surface. Whenever public health professionals or epidemiologists use disease registries with address information, consider the locations of toxic waste disposal sites, or look at their quality and water quality reports from monitoring stations, they work with geographic data. In the 1990s, the term *GI Science* was coined to distinguish the research field from GIS, whose technology builds on theories and techniques of spatial analysis and cartography that were relevant long before the innovations in digital computing made GIS possible. Several studies have contributed to the definition of GIS, *e.g.* Musa *et al.* (2013) define it as a computer system with the capacity to capture, store, analyze, and display geographically-referenced information, while Fradelos *et al*. (2014) see it as a spatial, digital data management system that can integrate, store, adjust, analyze and arrange geographically-referenced information. Fradelos *et al*. (2014) add that GIS can be described as smart maps that offer a simulation of the real world and which can generate interactive spatial or descriptive questions, analyze spatial data adapting and adopting them to the analogue sphere (printed maps and diagrams) or digital media (records of spatial data and interactive maps on the Internet). Akeh and Mshelia (2016) feel that GIS can be defined as a configuration of computer hardware, software and data specifically designed to capture, store, analyze, manipulate, edit, retrieve and display spatially-referenced data. In this paper, GIS is portrayed as a system for storing and managing data that have been identified according to location.

Like many other organizations, public health agencies and public/private providers or insurers of medical care services manage large databases that contain geographic information that can be meaningfully integrated based on location. The developments in hardware, software and database have brought new GIS users into the field explaining the diffusion of GIS into the public health sphere. The ability to visualize and explore health data interactively is a main advantage in public health analysis. A view, *i.e.* the computer display board that one can see on the computer screen, is a graphic representation of data. The extent of the view is always less than or equal to the addressable space in a dataset. In GIS, the spatial objects in the view and the tablets of attributes describing them can be directly linked. The analyst can access the two together and explore the relationships among attribute data in the table and the spatial representation of that data in the view.

Fletcher-Lartey and Caprarelli (2016) reviewed the application of GIS technology in the public health area and identified both successes and challenges. They confirm that geographical analysis allows researchers to interlink health, population and environmental data, thus enabling them to evaluate and quantify relationships between health-related variables and environmental risk factors at different geographical scales. The application of GIS in disease studies has furthered the understanding of the inter-

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section between person, place and time in outbreaks of infectious disease and the underlying social and cultural factors. Ruiz and Sharma (2016) looked at the application of GIS for public health in India, today equal to 17% of the world population, stressing that the implementation of geospatial technologies and methods for improving health is already widespread in many nations. Multiple data overlays and multivariate statistical analysis are used for geographical analysis of health data at different spatial scales. Najafabadi and Pourhassan (2011), for example, emphasize the use of visualization, data integration, spatial analysis and spatial modelling for cancer research, while Ruiz and Sharma (2016) report a large number of GIS-related categories besides demographic information, such as communicable diseases (parasitic, bacterial, viral infections of different kinds), non-communicable diseases (*e.g.*, trauma and cancer) and environ variables such as the quality of water and air.

GIS offer a flexible, computerized environment that facilitates exploration and analysis of old and new data, *e.g.*, by preparing and displaying maps of health information, which remains an important function of public health GIS applications. One can easily pan across a map, zoom in areas of interest or query a database to examine areas or events of special concern, thereby linked health information with social and environmental features to examine geographical associations. This makes the computerized map a product of exploring, viewing and analyzing spatial information. There is no perfect map, rather each map is just one of an almost infinite array of possible representations of spatial information. Juarez *et al*. (2014) demonstrate the use of GIS to support analysis of the complex interactions between health outcomes, health disparities and the environment and show that the mapping of health information can be used to visualize geographic patterns and temporal trends at levels varying from county to country.

GIS support public health analysts in reaching further than simply mapping and managing data. Specifically, spatial analysis covers a set of techniques requiring access to both locations and attributes of interest emphasizing that results of spatial analyses are not invariant when locations of the objects under study change. As such, spatial analysis covers a broad range of numerical methods that are useful, *e.g.*, when calculating distances between points, be they straight-line or curved. Although these functions are few in number, they are extremely important, while topological functions, such as spatial overlays, assessment of spatial relationships across groups of data and map comparisons are key to epidemiological analyses. Public health analysts will typically approach a database wanting to know what the main health problems are and where they occur. They might also wish to identify the places of interest health interventions finding out what kinds of problems occur there. By utilization of basic GIS mapping capabilities, Photis (2016) has shown that it is not only possible to provide significant insights related to such questions, but also to lead in the direction of improving health-related policy and planning issues.

Using GIS for health care planning in Jeddah city is still in its development stage. For example, Murad (2008) discussed the application of GIS for the catchment areas of health centres in Jeddah City using straight line allocations which define the areas based on proximity. In addition, Murad (2014) used Eculidean distance and drive-time analysis for evaluating accessibility to public health care centres producing an accumulative accessibility model that defines level of accessibility to every city district in Jeddah based on the distance by road. This paper presents a new GIS application related to hospitals rather than health centres applying GIS mapping capabilities for hospital planning in Jeddah City using thematic maps including classification of hospital size, health-related supply density and health care accessibility.

Materials and Methods

Spatial data

Spatial datasets are fundamental components of GIS. The success of health related GIS projects depends critically on having access to accurate, timely and compatible spatial data. For organizations embarking on GIS projects, spatial data can be viewed as both a cost and a resource. The development of spatial datasets is expensive; indeed well over half the cost of a GIS project goes to base creation, updating, and improvement, but these datasets are useful for addressing a wide range of issues related to policy and planning. Thus, their value extends well beyond the scope of the original projects for which they were created.

Cruz *et al.* (2013) emphasize that the availability of a wide variety of geospatial datasets requires new functions and tools to perform integrated analysis and visualization. They developed a semantic framework for geospatial integration, visualization and analytics, which considers two components, one for visualization and the other for analysis and support, the latter providing a suite of statistical models for spatial data exploration and multivariate analysis. ZIP codes, areal borders and roads form a template for representation that provides information useful for health-related analysis. Area health data are spatially *filtered* with respect to predefined zones and thus depend on the zoning system used. The database of the presented paper was created using ArcGIS software (ESRI, Redlands, CA, USA) to cover a large set of attributes including hospitals locations, road networks, polygon with population data, *etc*. Each GIS feature is joined with its relevant attributes. For example, the point feature of a hospital shapefile includes attributes such as hospital name, type, bed size, if it is public or private, location and surrounding area. On the other hand, road network file includes useful attributes such as road name, road length, driving speed/time, *etc*. These features and attributes can be collected and saved in the application geo-database for performing the required analysis and models.

Choropleth mapping

Area health data commonly refer to rates or ratios or other statistics with spatial applications. In these situations, choropleth mapping, where data values are displayed by colour patterns that fall into specifically assigned class intervals, is the preferred approach. Difference in the intensity of colours or patterns varying across the map signify the information available. A key issue in choropleth mapping is the choice of class intervals, variation of which can fundamentally change the message displayed. Most GIS offer a range of options for defining class intervals. A common way is equal interval classification where the range of data values, *e.g.*, maximum or minimum values, are divided into a fixed number of classes that each represents an equal interval of possible data values. Although this method works well for some distributions, it performs poorly if there are extreme values in the dataset. Choropleth maps and analytical results also vary with the number and size of the areal units involved. This is known as the scale effect. Small areas capture the underlying pattern of health events,

pagepress

showing fine-grained spatial variation, while local differences in large areas reduce such variations. A county-scale map cannot show differences among towns and neighbourhoods, for example, and state-level data hide disparities across counties. Wei *et al*. (2017) mention that choropleth mapping is an important exploratory spatial data analysis technique that has been extensively used to visually explore the spatial pattern of attribute distributions across regions. It is one of the most widely used methods to visually explore spatial distributions of demographic and socio-economic data. An essential procedure in choropleth mapping is determining class intervals to suitable group spatial units. A variety of classification methods have been developed with examples including interchange heuristics, class reparability, natural breaks, equal interval and quantiles. Choropleth mapping was used for displaying the hospitals in Jeddah City and the next section presents the outcomes and result of this approach.

Mapping health service locations

Preparing maps of health service locations is an important application. Rather than information covering one type of service, health planners want to know about an array of services that can support health and social welfare (*i.e*. jobs, education, child-care as well as about specific facilities dealing with specific activities, such as mental health, substance abuse, *etc*. To better integrate diverse health-related services, planners advocate the creation of service hubs sites with health and social service agencies located nearby (Cromley and McLafferty, 2012). However, the creation of datasets with multidimensional indicators of service needs often involves linking variables measured to geographic points like ZIP Codes. This linking process requires each variable to be estimated for a set of consistent zones with common spatial units, *e.g*., health needs also has qualitative dimensions called *perceived needs*. GIS can be exploited to view and analyze such dimensions among different population groups. For instance, scientists doing research on healthcare utilization, deprivation and cardio-vascular diseases carried out in the state of Kentucky, USA realized that the need to account for the patients' social status (housing quality, work, status, *e.g*., poverty) to correctly perceive their needs (Barcus and Hare, 2007).

There are 53 hospitals in Jeddah City, 38 (72%) of which are private and 15 (28%) public. This means that private hospitals are plying a major role in providing health services. The spatial distribution of all hospitals is shown in Figure 1A which indicates that the private hospitals are mainly located in the central and northern districts. Meanwhile, the public hospitals are located in the central districts. Each type of hospital has different beds capacity. Private hospitals (Figure 1B) are providing smaller bed sizes with the numbers ranging from 30 to 400 beds per hospital, while the public hospitals generally have a larger capacity ranging from 80 to 1,002 beds per hospital (Figure 1C). It can therefore be said that the public hospitals are providing large health services supply for patients but at limited locations in the city. The private hospitals, on the other hand, are distributed at several city districts but they have limited capacity.

Modelling health services density

Rather than focusing only on distance or travel time to the nearest service provider, one can compute density measures that describe the full range of providers in an area. Density refers to the number of providers available in relation to the local population in an area. One can define density in relation to predefined geographic zones such as the *container approach*, or within a fixed buffer distance of a point of origin - the *coverage approach*. A well-known container measure is the number of physicians per population ratio, which is widely used in analyzing access to care. Although this approach has traditionally been used, it has major limitations, *e.g*., the zones that underpin the density calculations are often arbitrarily defined and the political units differ in size, shape and socio environmental characteristics. *Container measures* ignore the availability of services across boundaries of region and do not consider the ability of people to address this type of constraints. It is therefore better to use coverage approaches that estimate the density within the overlapping areas of coverage. This kind of measures fit GIS better than the container approach.

When analyzing geographical access to health care in densely populated urban areas, kernel estimation can also be utilized. This tool calculates the density in a neighbourhood around particular features and it can be calculated both for point and line features. Possible uses include finding the density of houses, the risk for crime, alternatively also for roads or electrical power lines influencing a town or wildlife habitats. The population field can be used to weigh some features more heavily than others, depending on their meaning for the study being carried out. In addition, one point can be allowed to represent several observations. For example, one address might represent a condominium with six units, or some crimes might be weighed more heavily than others in determining the overall crime level. For line features, a divided highway probably has more impact than a narrow dirt road, and a high-tension power line has more impact than a standard electric pole (ESRI, 2018). Conceptually, when a smooth curved surface is fitted over a point, the surface value is highest at the location of the point and diminishes with increasing distance from it, reaching zero at the search radius distance. At first, geocoding of service providers to point locations should be created. A circular window scans the map, and the kernel density of service providers is computed within each circular window. Kernel estimation depicts the density of service providers (number per unit area) as a continuous spatial variable, with peaks representing areas of high geographical access and valleys indicating areas of poor access. For example, kernel density estimation has been used to investigate children's geographical access to primary care physicians in Washington, D.C. in USA (Cromley and McLafferty, 2012). In addition, Murad (2018) produced kernel density models for defining the spread and concentration of demand for health service facilities in Jeddah City. Density estimates can be assigned to individuals and aggregated to show differences in access among population groups or they can be used in individual-level statistical models. By computing a kernel density surface to represent population and dividing provider density by population density, one can find out the availability of services in relation to population. The algorithm used to determine the default kernel search radius, also known as the bandwidth, is as follows: i) Calculate the mean centre of the input points. If a population field other than is *none* selected, this plus all the following calculations, will be weighted by the values in that field; ii) Calculate the distance from the (weighed) mean centre for all points; iii) Calculate the (weighed) median of these distances (D_m); iv) Calculate the (weighed) standard distance (SD); and v) Apply the following formula to calculate the bandwidth:

$$\text{Search Radius} = 0.9 * \min\left(SD, \sqrt{1}\frac{1}{\ln(2)} * D_m\right) * n^{-0.2} \quad \text{Eq. 1}$$

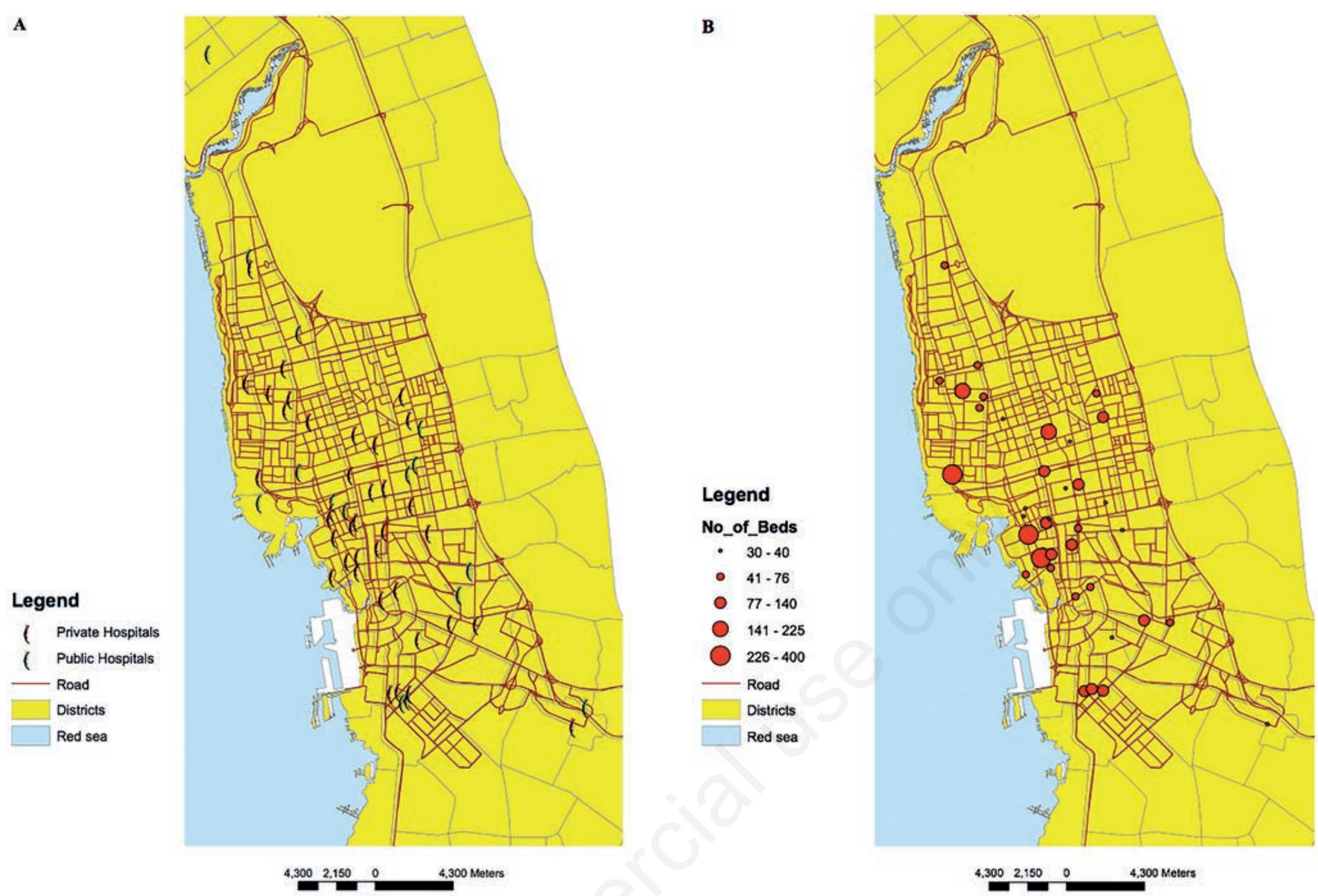
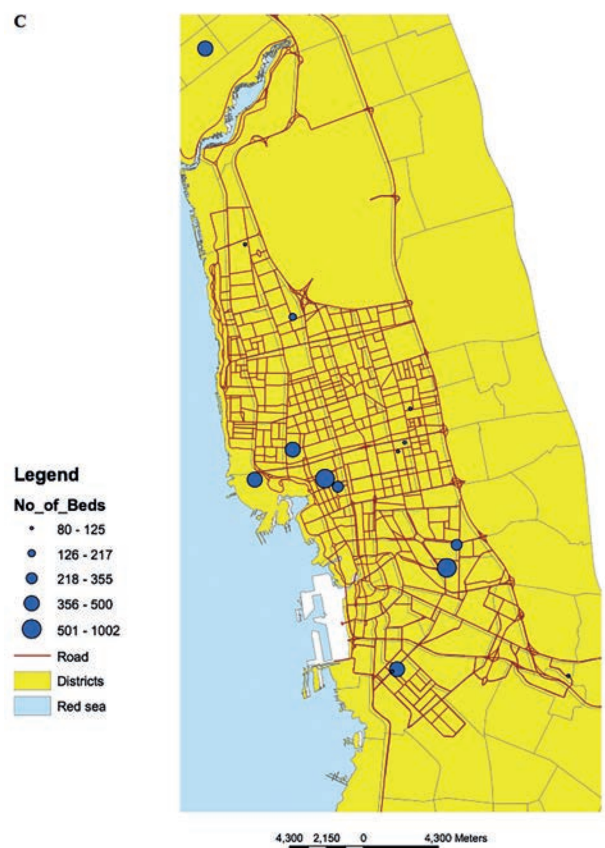


Figure 1. (A)The distribution of hospitals in Jeddah City; (B) Classification of private hospitals with respect to bed size in Jeddah City; (C) Classification of public hospitals with respect to bed size in Jeddah City.



where SD is the standard distance, D_m the median distance, n the number of points if no population field is used, or if a population field is supplied equal to the sum of the population field value.

The presented paper produced produced kernel density for both public and private hospitals in Jeddah City. Figure 2 presents the output models based on number of beds in private and public hospitals. Both models indicate that there is a clear need for more hospitals in the northern part of the city because this area has a remarkably low density of hospitals beds. The health authority in Jeddah should prepare immediate plans for allocating new public and private hospitals in the northern part of the city. This type of analysis help health planners to find the parts of the city that provide larger hospital services and the parts that have shortages.

Analyzing access to health services

Access is a multidimensional concept that describes people's ability to use health services when and where they are needed, It describes the relationship between attributes of service need and the characteristics of service delivery systems. There are five important dimensions of access that should be identified: i) Availability defines the supply of services in relation to needs (answering the question if capacity and type of service meet the

pagepress

health care needs); ii) Accessibility describes geographical barriers including distance, transportation, travel time, and cost (highlighting the geographical location of services in relation to population needs); iii) Accommodation identifies the degree to which services are organized to meet clients' needs, including hours of operation, application procedures and waiting times; iv) Affordability refers to the price of services with regard to people's ability to pay (income levels and insurance coverage are critical aspects of affordability); and v) Acceptability describes the clients' views of health services and how service providers interact with clients (encompassing barriers linked to gender, culture, ethnicity and sexual orientation that affect the willingness to use particular health service facilities and the sense of comfort and satisfaction received).

Access to health services can be classified into two categories: revealed access (actual use of health care services in each location) and potential access (ease of accessing services based on current conditions) (Gao *et al*., 2016). A fundamental aspect of health care utilization patterns is the *distance decay*, which signifies the tendency for interaction with service facilities to decrease with increasing distance. Distance decay is a consequence of the added cost of having to travel far, the time it takes translated into the willingness to travel. The role of geographical access also depends on variables concerning the population under study, as people characterized by limited mobility, for example, are more likely to use the nearest health care facility. An extensive study in San Antonio, TX, USA recording the movement of low-income people, their children and disabled people supports that claim (Matthews *et al*., 2005). Characteristics of the local environment also affect the role of distance in people's use of health care services. Crime, lack of safety and environmental pollution can inhibit use of services even when located nearby. The impact of geographical access on health is increasingly under examination in various countries with an unequal distribution of health service resources. Evaluating geographical healthcare accessibility in residential areas provides critical information to decision-makers. For instance, it allows the identification of areas having lower or higher levels of access (Gao *et al.*, 2016).

One of the simplest ways of measuring potential access is to calculate the distance from the people needing health service to the nearest service provider. This population dataset can either be: i) a point dataset that contains residential locations of people in need of service; or ii) an areal dataset with counts of resident population by area.

The larger the average distance, the weaker the geographical accessibility. In addition to average distance, there is also the frequency distribution of distance, which is a graph that shows the number of people living within a distance range with respect to their nearest services facility. Analyzing the distribution of distribution can offer potent insights regarding the equality and inequality of geographic access among population groups. There are many ways of measuring distance to health location which include: i)

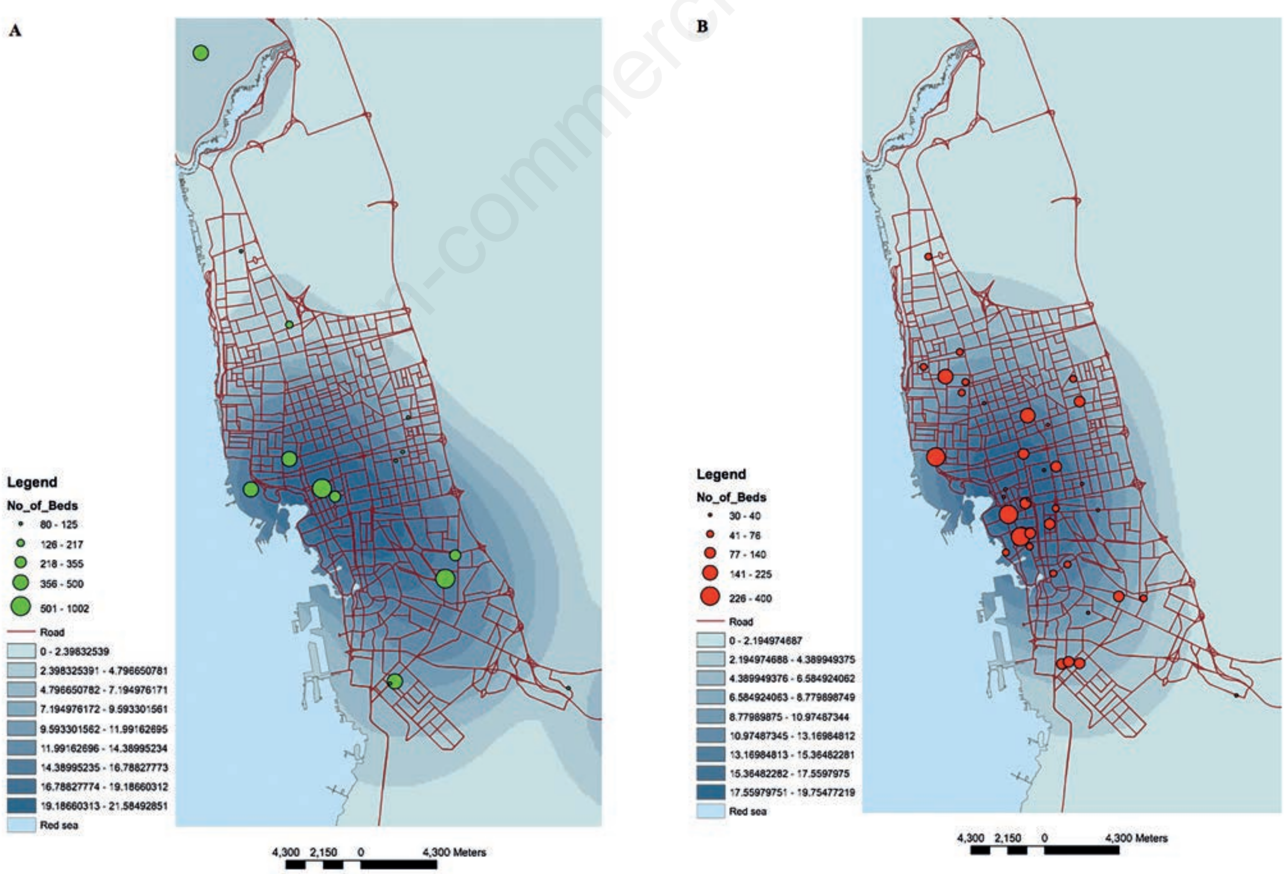


Figure 2. (A) Bed density in public hospitals in Jeddah City; (B) Bed density in private hospitals in Jeddah City.

Spherical distance which measures the distance along a great circle connecting two points (used for small-scale investigations); ii) Euclidean (straight-line) distance, which works with projected geographical coordinates, however, it fails to consider transportation routes and barriers to movement; iii) Manhattan metric which used to calculate distance with areas that follow grid pattern road network; and iv) Network distance which computes the length of the shortest path along a transport network.

The application presented with regard to Jeddah City covers Euclidean (straight-line) distance and network distance for identifying accessibility to health services. Figure 3 presents the results of Euclidean-based accessibility models for private and public hospitals. This Figure shows that patients that live in the northern and eastern part of the city have a low accessibility status, which means that additional hospitals in these districts are highly recommended.

One of the simplest ways of measuring potential access is to calculate the distance from the population in need of service to the nearest service provider. Although distance is a fundamental indicator of geographical access, travel time, cost, transportation access and perceived distance are often much more relevant to health care utilization. Using GIS, one can estimate travel time along road networks, taking into account average speeds and speed limits on different classes of roads as well as physical barriers to travel. To determine the travel time between two points, one should identify the route connecting those points and sum the estimated travel times along each road segment. Travel time provides a better indication of geographical barriers to health services than does travel distance, since, by definition, travel time incorporates access to transportation. Mode of transportation is also important in estimating travel times. Most GIS include tools for calculating network distances that follow a street, bus or rail network. Given a starting node and an ending node, the GIS will compute the length of the shortest path along the transport network and the result used as the network distance. Such distances offer a good approximation of the actual distances people must travel to obtain health services. The application in Jeddah City presented produced a 30-miutes drive time service area for public and private health services in the city. Figure 4A presents the drive time to public hospitals, which indicates that there are several parts in Jeddah, mainly in the northern, central and eastern city districts, that fall outside the 30-minutes limit. Patients living in these districts must travel longer time in order to reach their nearest public hospital, which means that new additional public hospitals should be recommended for these parts of the city. Figure 4B shows the scenario for the private hospitals service area. The results of this type of hospitals show a better coverage compared to public hospitals. However, additional private hospitals are also recommended for northern city districts.

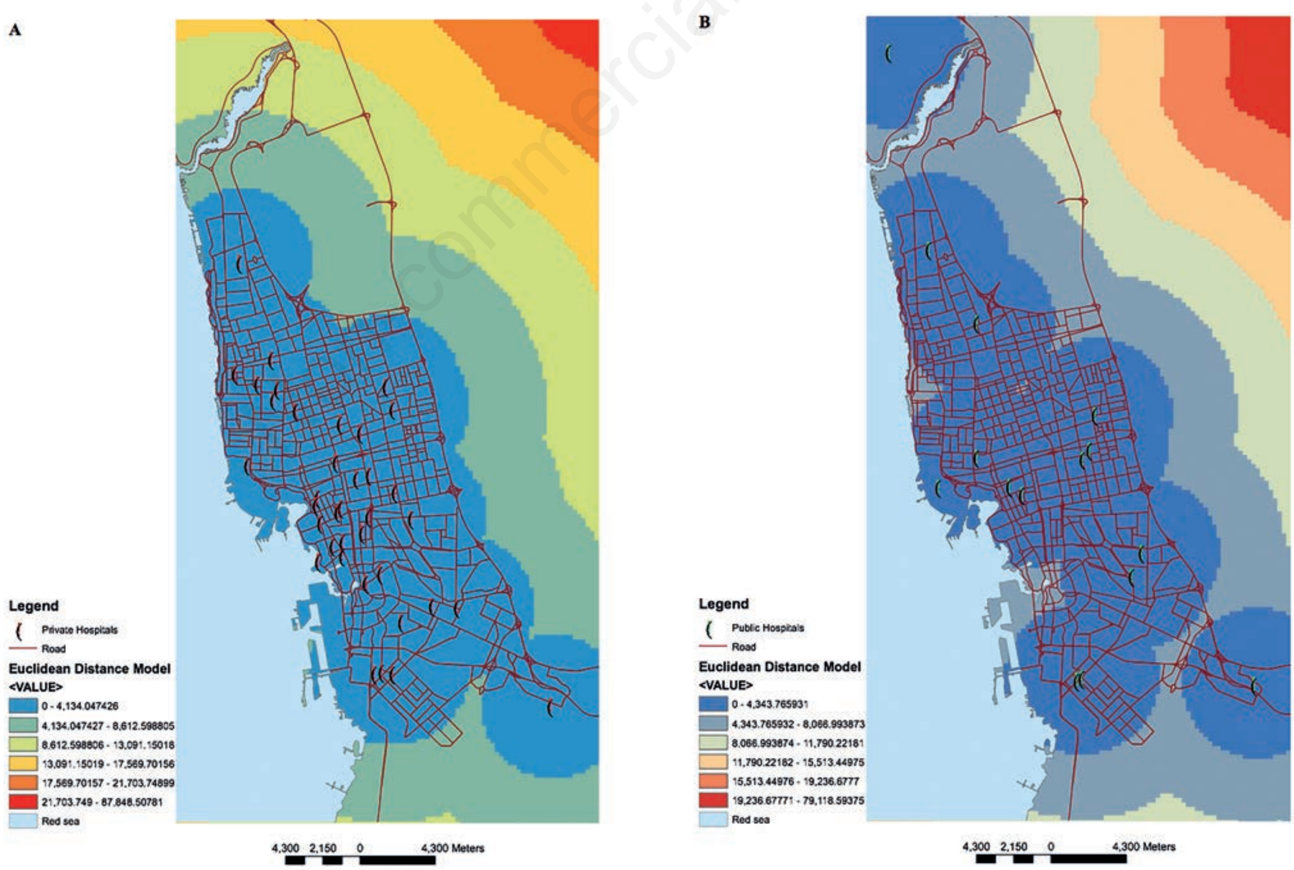


Figure 3. (A) Euclidean based accessibility model for private hospitals in Jeddah City; (B) Euclidean based accessibility models for public hospitals in Jeddah City.

Discussion and Conclusions

Information about health services typically exists in tabular form, as lists of service providers and their addresses. Maps of health service locations are not only an important GIS application area, but would also provide a more user-friendly approach as such maps display service location patterns that are not evident from written information. Many health agencies now use GIS to manage spatial information about services, but finding out what types of services exist in an area, and where they are located is still not straightforward. However, the preparation of dedicated maps would provide facts about service locations and availability visualizing spatial matches between service needs and resources. This should also be useful for public health professionals who are often faced with the task of investigating disease clusters, unusual concentrations of health events in space and time.

As GIS technology develops, innovative spatial statistical methods are being linked with GIS to analyze the spatial clustering of disease in populations and to assess changes in health status and disease prevalence over time. Carroll *et al.* (2014) report that the development of increasingly sophisticated GIS has provided a new set of tools for public health professionals to monitor and respond to health challenges. These systems can help pinpoint cases and exposures, characterize spatial trends, identify disease clusters, correlate different sets of spatial data and test statistical hypotheses. These analyses can be aided by visualization and mapping of data provided via web services or a user interface. There are many approaches to delivering GIS functions based on various sources of public health data, including geocoding, integration of data sources, and cluster detection. Mapping of health data is commonly achieved through dot maps, choropleth maps, and also isopleth (colour gradient) maps. Some GIS or spatial statistical methods seek to perform kernel-based smoothing to estimate risk maps, visualize disease risk according to a statistical model, or compare one feature with another. While the ability to zoom and pan to navigate maps is a common interactive feature enjoyed by users, more advanced systems contain interactive controls enabling users to retrieve information about selected items or regions, visualize outcomes of arbitrary queries as well as controlling visualization options and temporal ranges of data returned.

Bui and Pham (2016) underline that the use of spatial information becomes popular with the integration of GIS and statistics package in processing health data. Spatial location in maps can be defined by geocoding tools that enriches the description of a location, most typically a postal address or place name, or provide a matching graph or statistic table attributing special data. Srinath *et al.* (2013) show that GIS can map and analyze the spread of disease in various environments. They used GIS to illustrate and understand the association between environmental factors and

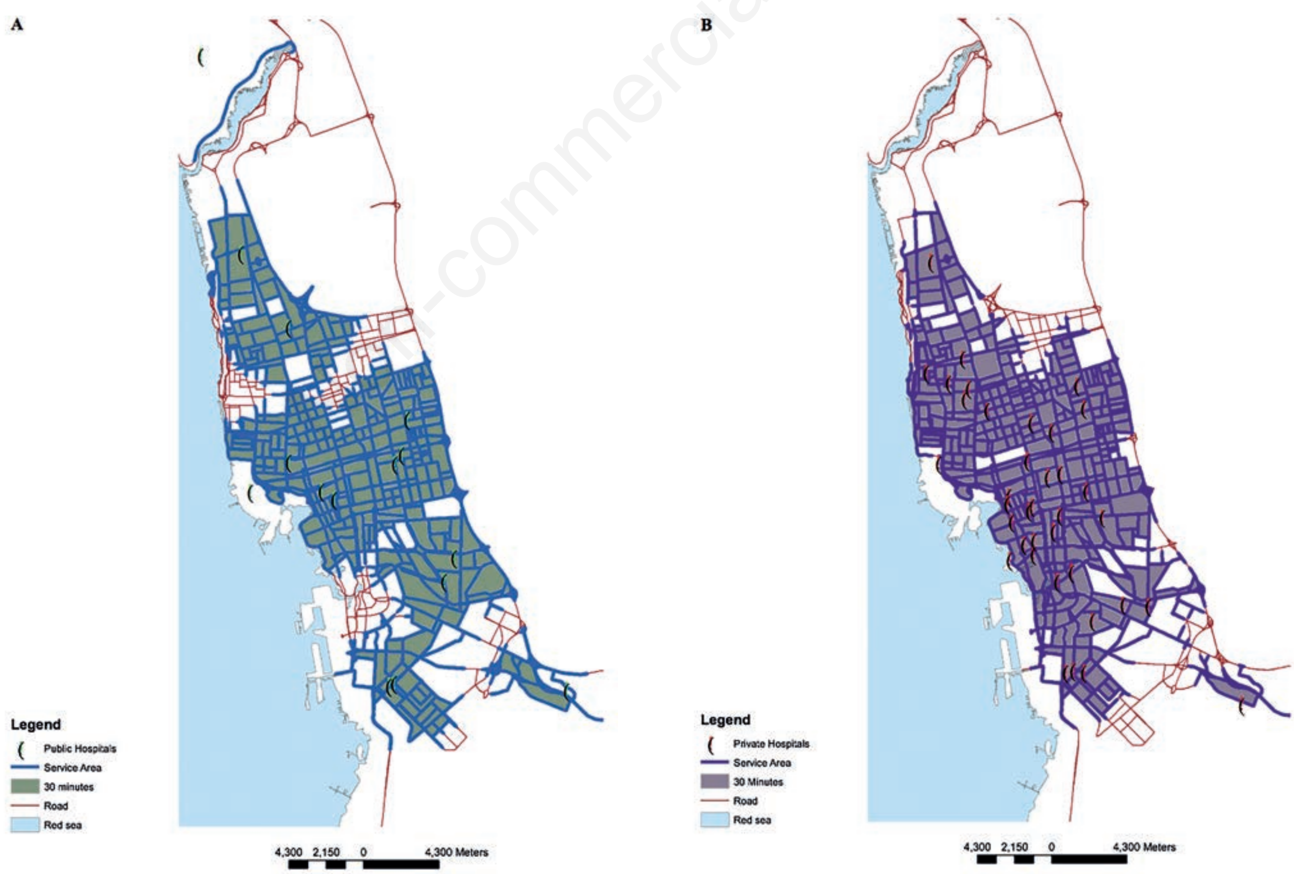


Figure 4. (A) Network based accessibility models for public hospitals in Jeddah City; (B) Network based accessibility models for private hospitals in Jeddah City.

infectious diseases in Texas, USA emphasizing that spatial methods improve support epidemiological research motivated by the strong correlation between disease spread and ecological factors.

GIS software systems enable public health analysts to do more than simply manage and map data. For example, support investigations requiring dedicated, spatial analysis functions and tools, some of which discussed in this paper. This is shown by this communication, which proposes several GIS models for hospital planning in Jeddah City covering both public and private facilities. The models were produced using ArcGIS software using several functions including choropleth mapping, kernel density, Euclidean (straight-line) distance, and drive-time service area. Each of these models not only help health planners in evaluating existing hospital locations, but can also be used for predicting future hospital locations. In order to produce these models a geo-database was created for public and private hospitals which includes points, lines and polygon features. Each feature is linked to its relevant attributes including hospital bed size, road travel time and population size for city districts. The health authority in Jeddah City may use these models to allocate new hospitals at areas characterized by poor hospital accessibility results.

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