Optimising the spatial distribution of fire stations in the urban sphere, a case study of Greater Accra Metropolitan Area, Ghana

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Key words: Multi-criteria Analysis, Geographic Information System, Fire Response Management, Urban Growth

SUMMARY

Instant response to fire events is important for emergency response since delays in arrival can have serious repercussions in terms of cost, damage, and death. However, the growing urban interface in cities poses a difficulty in developing and sustaining efficient emergency response procedures. As a result, one of the primary objectives of planners is to ensure that all service areas are properly covered so that fires may be addressed within an acceptable response time or distance. The goal of this research was to optimize the geographic distribution of existing fire stations in the Greater Accra Metropolitan Area through spatial coverage and network analysis. The spatial coverage area of existing fire stations was analyzed using the buffer and network analyst tool in the ArcGIS environment. By this, the research identified pockets of areas within the study area that are not covered by existing fire stations through the use of international recognized fire standard codes by the National Fire Protection Association (NFPA). Additionally, to optimize the geographic distribution of fire service stations, the study explores the use of multi-criteria analysis by using the weighted overlay tool in ArcMap to find the best locations to cite new fire stations. In summary, geospatial tools have been demonstrated as an efficient tool in optimizing the geographic distribution of fire service stations in GAMA.

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1. INTRODUCTION

1.1 Background of Research

Fire is a basic element used frequently in everyday activities. The tendency of one of this essential tool to revert and cause damages cannot be underplayed, as improper handling and use of fire has led to several accidents in homes, offices, schools, and other public places with very serious repercussions. The occurrence of fire outbreaks in our urban community has become a growing menace in our society. In Ghana, fire incidents have become a regular occurrence, with thousands of lives and millions of dollars lost every year. Hardly a day passes without news of a fire outbreak in some part of Ghana, causing fear and panic among the people. Classic examples are the fire occurrences in major trading centers such as the Bantanma and Mokola Market. The country keeps incurring huge losses in terms of property damage and resources lost because of fires; for example, in 2013 approximately 11,000 Ghanaians were affected by fire and explosion, and the cost of these type of incidents was approximately $7 million (Tulashie et al., 2016; Simpson 2010). Anaglatey (2013), observed that one of the main causes of fire outbreak in Ghana has been electrical problems resulting from faulty wiring. As the population increases, human activities involving the use of fire also increase, and more people tend to become careless while handling fire. Owusu-Ansah (2018), noted that Ghana's population increases yearly by a factor of 6.7%.

Urbanization could be another reason for the increase of fire incidents in Ghana. This is because most people in rural areas move to big cities in search for greener pasture. Ghana, like most developing countries, is undergoing rapid urbanization. This rapid increase in urban population has exerted severe pressure on most cities' limited infrastructure, the consequence of which includes the proliferation of informal and slum communities. In general, most dwellers in these settlements have become vulnerable to a wide range of disasters, particularly fire hazards. This puts a tremendous amount of pressure on urban cities and leads to congestion in human settlements, hence creating more slum areas.

The mission of the Ghana National Fire Service (GNFS) is to protect life, property, and natural resources from fire and other emergencies. With increasing demands, the fire service must utilize the best tools, techniques, and training methods to meet public expectations. Risk management, preparedness, and mitigation have taken on new importance with challenges facing the fire service today (ESRI, 2006). Effective response cannot be continually achieved without adequate planning and preparedness. One of the emerging tools that is helping the fire service optimize its emergency services delivery is geographic information system (GIS) technology. GIS supports planning, preparedness, mitigation, response, and incident management (Shekhar et al., 2008). Much of this essential information during fire outbreaks has a spatial component, such as extents and locations of damaged areas, the locations of resources and services or safe transportation routes. Such geographic information, or spatial data, are useful in all phases of emergency management (Cutter 2003; Al-Khudhairy 2010). There are, however, challenges to overcome in the utilization of spatial data and geographic information systems (GIS) in the context of emergency management (Zerger & Smith, 2003; Mansourian, 2005). One such challenge is providing decision makers and field workers with access to data that are accurate and sufficiently up-to-date for their specific purpose. In this light, spatial analytics have for some time been used by policymakers and practitioners to capture spatial coverage and geographic accessibility (Kiran et al., 2020). Many of these studies have employed location models to evaluate the capacity and efficiency of emergency response through linking factors such as cost, time, population/dwelling density, socioeconomic conditions and political interests (Hecht et al., 2019; Kiran et al., 2020). However, a limited number of studies have drawn on estimates of future population growth to inform location decision choices for new fire stations in areas which are likely to generate higher future demands for emergency service (Donner et al., 2008).

Geographical Information System (GIS) is therefore a tool which assists the decision maker in the selection of various sites for any proposed project (Jankowski, 1995). Finding an optimal site for a fire service stations is influenced by many factors and this this problem can be considered as a spatial multicriteria decision analysis (SMCDA) (Nyimbili et al., 2018). Thus, this study provides framework of an integrated GIS approach by using network analysis approach for appropriate siting of fire service stations in an urban area. GIS can provide an opportunity to identify suitable site by encountering various criteria. Hence, this paper seeks to explore existing literature and analyse spatial data to optimize suitable locations of fire service stations in Greater Accra Metropolitan Area by using geospatial tools.

1.2 Problem Statement

Fire stations play a central role in protection and response activities as part of emergency management services in cases of fire outbreaks. With the rising urban populations and city expansions, the demand for more fire services increases. It then becomes critical to effectively plan the location of emergency facilities to adequately service the population and ensure the protection of lives and infrastructure (Nyimbili et al., 2018). Emergency planning has been stimulated by recent improvements in geo-technological areas in which an increasing amount of spatial data is required for complex decision-making by emergency responders (Erden, 2012). A quick and agile response, are two critical factors that determine the efficiency of operational response to emergency call-outs. Timely response is paramount to ensure the safety of people, and protection of properties and the physical environment (Challands, 2010).

In the Greater Accra Metropolitan Area (GAMA), the traffic situation is more intense due to the large urban space, high number of cars, and bad road networks which can severely influence the accessibility of fire stations. In this light, traditional techniques for determining station sites by simulating fire occurrences within districts are inadequate to satisfy criteria in these scenarios. Hence the need to broaden innovative research approaches such as the use of GIS tools for optimizing the location of fire stations. The timely response to calls for emergency services continues to challenge fire agencies in Ghana, especially in responding to rapidly growing metropolitan areas experiencing significant population growth and restructuring in urban form. The optimal distribution of fire stations that aligns with the changing demand for services is a vital operational tool to maintain timely response with minimum resources. Therefore, the identification of the most suitable locations to site fire stations to establish an equitable fire network coverage is a major goal for fire agencies.

In an emergency situation, relevant information about involved elements is essential to save lives. This information ranges from demographic data, weather forecasts and sensor data, available transportation means, presence of helpful agents, land use and cover statistics or values, etc. Moreover, the emergency management process is dynamic as it involves several definite steps, described in standard procedures from which the emergency officers such as medical personnel, fire service and the police are able to get to the location of incidents within the shortest possible time to save lives and property. However, limited research has been made on how fire service stations can be distributed efficiently in Ghana. This paper therefore seeks to fill in the gap in literature to efficiently distribute fire service stations within a highly urbanized area in Ghana by employing geospatial tools.

1.3 Research Objective

The main objective of this research is to optimize the geographic distribution of fire service stations in the Greater Accra Metropolitan Area. In an effort to answer the highlighted main objective research questions, the following sub objectives have been developed to aid optimize the geographic distribution of fire stations.

- ✓ To analyze the spatial distributions of fire stations in GAMA
- ✓ To determine the service area covered by existing fire stations in GAMA
- ✓ To predict areas suitable for citing fire stations in GAMA

1.4 Importance of Optimizing Location in Emergency Management

Location science has a long history, and the literature on location selection has grown as academics have become more interested in it (Mara et al., 2021; Şen et al., 2011). Several research articles have resulted in the classification of location science into various sub-categories, one of which is in locating emergency facilities. Police, fire, and emergency responders are all responsible for enhancing public safety, and they all share the goal of attending to public cries for help as fast as possible in order to prevent loss of life and injury (McEntire, 2015). Fire stations are positioned as part of a system that aims to provide a consistent level of service to all households while accounting for risk and service time (Kahanji et al., 2017). Hence, the number and placement of fire stations have a major impact on the effectiveness of emergency response during fires (Lui et al., 2006).

According to research findings on fire incidents in Accra (Appiah, Damnyag, Blay, & Pappinen (2010); Forkuo & Quaye-Ballard, 2013; Norman, Awiah, Aikins, & Binka, 2015), the Ghana National Fire Service has been unsuccessful in rapid response of fire incidents due to the atrocious nature of road networks, poor road maintenance practices and uncontrolled human and vehicular traffic. Each year, these factors frequently result in the loss of vast quantities of capital resources in the event of a fire outbreak. These factors tend to influence the rate at which Ghana National Fire Service responds to the public whenever their services are required. As a result, the service is perceived as being unable to carry out their tasks as planned. Thus it is crucial that, fire stations are properly situated; in an emergency, the fire department is expected to get at its intended location in less than 5 minutes (Şen et al., 2011).

1.5 Fire Incidents in Ghana

Fire incidents in urban environments is one of the most prevalent problems in both developed and developing countries including Ghana (Addai et al., 2016). Every year, a vast amounts of property and lives are tragically lost due to fire outbreaks and this not a new phenomenon in Ghanaian history (Addai et al., 2016; Anaglatey, 2013, Boateng, 2013). For example, the fire that consumed Ghana in 1983, caused a serious food crisis and has become a key point of reference in the country's history (Okyere, 2010). According to Anaglatey (2013), the problem of fire breakouts in Accra is exacerbated by congestion because not only are accessible roads blocked by houses, but fire hydrants are also concealed by these structures. Drysdale (2011) also contributes by stipulating that, the dynamics of fire incidents within Accra need a rapid response by fire and rescue services regardless of fire protection measures put in place by fire regulating agencies. Most of these fires occur at gas stations, markets, institutional buildings, and densely inhabited areas where slow-moving traffic is a major issue for the fire tender driver and crew (Addai et al, 2016; Fleming, 2009; Norman et al, 2015). GAMA's rapid urbanization has created a number of new problems in terms of the availability and architecture of urban public service infrastructure (Korah, 2021). The diverse distributional patterns observed in urban environments within megacities result in varying fire risk scenarios. In recent times, statistics on recent fire incidents rates is discussed below.

Period (Jan-Oct)	Domestic Fires	Bush Fires	Total Fire incident cases	Casualties Recorded
2019	1,822	608	4,623	222 (died) 1,125 (injured)
2020	1,910	1,220	5,355	

Table 1. **Fire Incident Statistics in Ghana from 2019-2020**
Source: Safo J.A, Daily Graphic Online (2021)

From Table 1, Ghana has experienced a rise in fire incident rates from 2019 to 2020. From January to October of 2019 and 2020, domestic fires accounted for 39.63% and 35.67% of all fire breakouts. According to the Ghana National Fire Service (GNFS), the causes of the fire outbreaks were segregated into 7 categories, that is: as domestic, industrial, vehicular, institutional, electrical, commercial and bushfire (GNFS, 2021). In an interview with the Daily Graphic, the GNFS's Public Relations Officer (PRO), Divisional Officer II Ellis Robinson Okoe, blamed the surge in fire outbreaks on a failure to follow fire safety guidelines. He also said the lockdown was to blame for the surge in domestic fire incidents during the time period. According to him, because a lot of people were obliged to stay at home during the spread of the pandemic, it resulted in over 272 domestic fire breakouts (Safo, 2021). The Greater Accra Region however recorded over 662 fire incident cases in the year 2020 (GNFS, 2021). Mr Okoe also reiterated that the public should be familiar with the nearest fire stations in their vicinities to be able to access them easily when there is an emergency. This however a good idea, is not feasible since there are only 18 existing fire stations situated in GAMA which comprises of 28 districts, hence some districts may be vulnerable in the event of a fire outbreak.

2. GIS IN FIRE RESPONSE MANAGEMENT

2.1 The use of Geographic Information Systems (GIS) for citing fire stations

GIS is a major tool for organizing, displaying, and analyzing data in order to make intelligent choices (Drobne et al., 2009). GIS permits geographically referenced information to be stored, edited, manipulated and analyzed to generate interpretative maps relevant for decision making (Barnett et al., 1993). Hence, it is widely utilized in areas such as land suitability, urban planning, natural risk management, water resources management, amongst others through spatial analysis (Malmir et al., 2016). Spatial analysis has played a major role in the above sectors due to its strong dynamic representation technology and analytical methodologies. To add to this, there has been a long history of research on fire station site selection and spatial optimization using GIS tools. This includes a research by Hogg (1968), who noted that the key to fire system analysis is determining the optimal number of stations and their most effective locations in order to reduce losses, whereas Marsh (1999), found that the most significant criterion of fire station location should be the minimum emergency response time. This component served as the basis for a fire station site selection model, which was further expanded by Plane and Hendrick (1977), who used reaction time as the coverage criteria to apply location set covering problem (LSCP) theory to the issue of site selection. Additionally, Erden et al., (2010) and Chaudhary et al., (2016) used the Analytic Hierarchy Process (AHP) and GIS to perform site selection and optimization assessments in various areas and cities (GIS). Murray (2013) and Chevalier et al., (2012) have also utilized the Maximal Coverage Location Problem (MCLP) model to fire station site selection. Badri et al., (1998) developed a multi-objective mathematical programming technique that takes into account travel time and distance, as well as cost, policies, and other variables while Yang et al., (2007) used fuzzy multi-objective programming in conjunction with a genetic algorithm to identify fire station sites. Thus, several studies conducted throughout the world have proven the effectiveness of employing GIS-based suitability models for site selection and facility allocation in the urban planning process.

Furthermore, GIS provides data layers and images of an impacted region in an emergency situation, emergency responders may gain a holistic perspective of the situation by combining damage and affected area information (Abdalla, 2016). In essence, GIS provides the platform for the creation of maps for emergency response. Maps are extremely useful since they can show you where issues exist as well as the people and locations that may be affected by them at a glance. Also, in recent time's geospatial data has become increasingly available, thanks in part to an increase in geographic measurement driven by new technologies such as GPS, Lidar, and others with real-time sensors that record spatial data for spatial analysis.

2.2 Network Analysis for Determining Service Area Coverage

The network analysis tool can be described as a system of interconnected components such as lines (edges) and points (junctions) that enables the solution of network problems such as determining the best route in the city, locating the nearest emergency vehicle or facility, establishing a service area surrounding a place, or selecting where to cite facilities (Evans & Minieka, 2017). Network analysis has a significant role in geographic information systems (GIS), which reflects the first GIS data models that were developed, its extensive applicability across domain areas, and its future potential value (Keenan et al., 2019). Network analysis is a basic spatial representation that can properly represent a wide range of interactions. The most used is the ArcGIS Network Analyst extension which enables the user to solve common network issues such as determining the best route across a city, locating the nearest emergency vehicle or facility, categorizing a service area around a location and deciding which facilities to open or close (ESRI, 2021). In using the network analysis tool it aids to calculate accessibility in terms of travel time of distance. In addition, the network analysis tool generate a network service area. This is a region that includes all accessible roadways, that is, streets that fall within a certain susceptibility threshold (ESRI, 2021). For example, a first responder's 8 minute service area comprises all road networks that are within 8 minutes of that facility.

Network Service Analysis employ Dijkstra's algorithm (ESRI, 2021). The coverage area is calculated based on a subset of connected edge features within a certain trip distance or journey duration. The edges are entered into a triangulated irregular network (TIN) data structure to generate travel areas. The network distance along the lines is used to calculate the height of the sites inside the TIN. Locations that are not traversed by the service area are assigned a considerably higher height value. With this TIN, an area-generation method is utilized to carve out regions containing areas between the provided break values (travel time or travel distance).

Many studies have been done throughout the world that employ GIS-based suitability models for site selection and facility allocation in the modern planning process (Gbanie et al., 2013). In citing emergency services such as fire stations, response time analysis may be conducted by combining a fire stations and street shapefiles (Rodriguez et al., 2020). Street data layer is represented in GIS as a sequence of intersecting lines on a map, resulting in a GIS street network (Rodriguez et al., 2020). Each segment of street line between junctions comprises attribute information such as road type, distance, and travel speed (miles or kilometers per hour) (Boeing, 2017). In Ghana this information can be accessed freely by using Open Street Map provided by ESRI. Although buffer analysis can be used to determine accessibility, it does not take into consideration the means of travel from a point of interest. This limitation in buffer analysis is rectified by the network analysis tool by identifying accessible road network from the point of interest to surrounding areas. Thus, by combining road network data with the locations of fire stations and trip time, network analysis can be performed in a specified study area.

2.3 Conceptual Framework

GIS in making effective decision was used. Spatial decision analysis is one technique used to help decision makers evaluate many factors. It is used to rationally analyze and compare various criteria, which are frequently contradictory, in order to make the best conclusion feasible. Most of the issues within the urban environment are geographical in nature, therefore using GIS has a significant influence in effective management. To resolve spatial urban issues is frequently characterized by a vast number of viable options. The use of a GIS is a technique that converts and integrates geographical data and value judgments in order to address location suitability issues. This is accomplished by taking into account geographical data models, the spatial dimension of the evaluation criteria, and choice alternatives. Hence, the conceptual framework model used in the study is Figure 1.

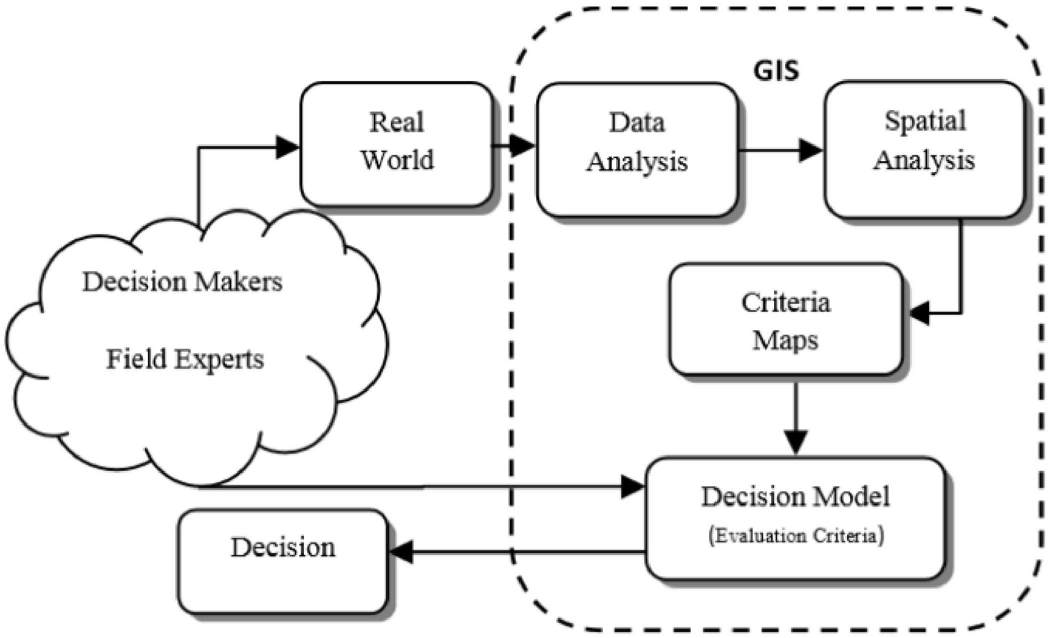


Figure 1: Conceptual Framework underlying the study

From Figure 1, Siobhan & Ellis (2019), define GIS-MCDA as a more robust criteria-based technique than a standard binary or 'coincidence' analysis. The model takes a static approach to decision making from decision makers. According to the concept in Figure1, decision makers and field makers are relevant stakeholders who make decisions on where facilities should be distributed geographically within a region of interest. Data from real-world settings, such as population density, elevation, and accessibility, can be converted for data and geographic analysis using geospatial technologies. Criteria maps can therefore be created by integrating the various essential components in facility siting and assigning weights to each component. The criterion maps may be used in decision modeling to help decision makers make educated judgments about where to locate a facility. In a nutshell, from figure 2.1, GIS allows decision makers and field experts to manage numerous values of different criteria and spatial data at the same time, allowing for more in-depth decision-making. In addition statistical models, such as AHP and FAHP, can be included into a GIS-MCDA, enhancing the analysis's reliability and overall relevance. However the premise adopted from the model in Figure 1 is using GIS tool to create criteria maps to aid in decision making by field experts for citing fire stations in GAMA.

2.4 Study Area

The Greater Accra Metropolitan Area (GAMA) is the most urbanized within the Greater Accra Region comprising of 28 districts. It is shares boundaries with the Awutu Efutu Senya District to the east, Akwapim South District to the North, Dangbe West District to the West and the Gulf of Guinea to the South (Accra Metropolitan Assembly, 2017). The map of GAMA showing major roads is seen in Figure 2

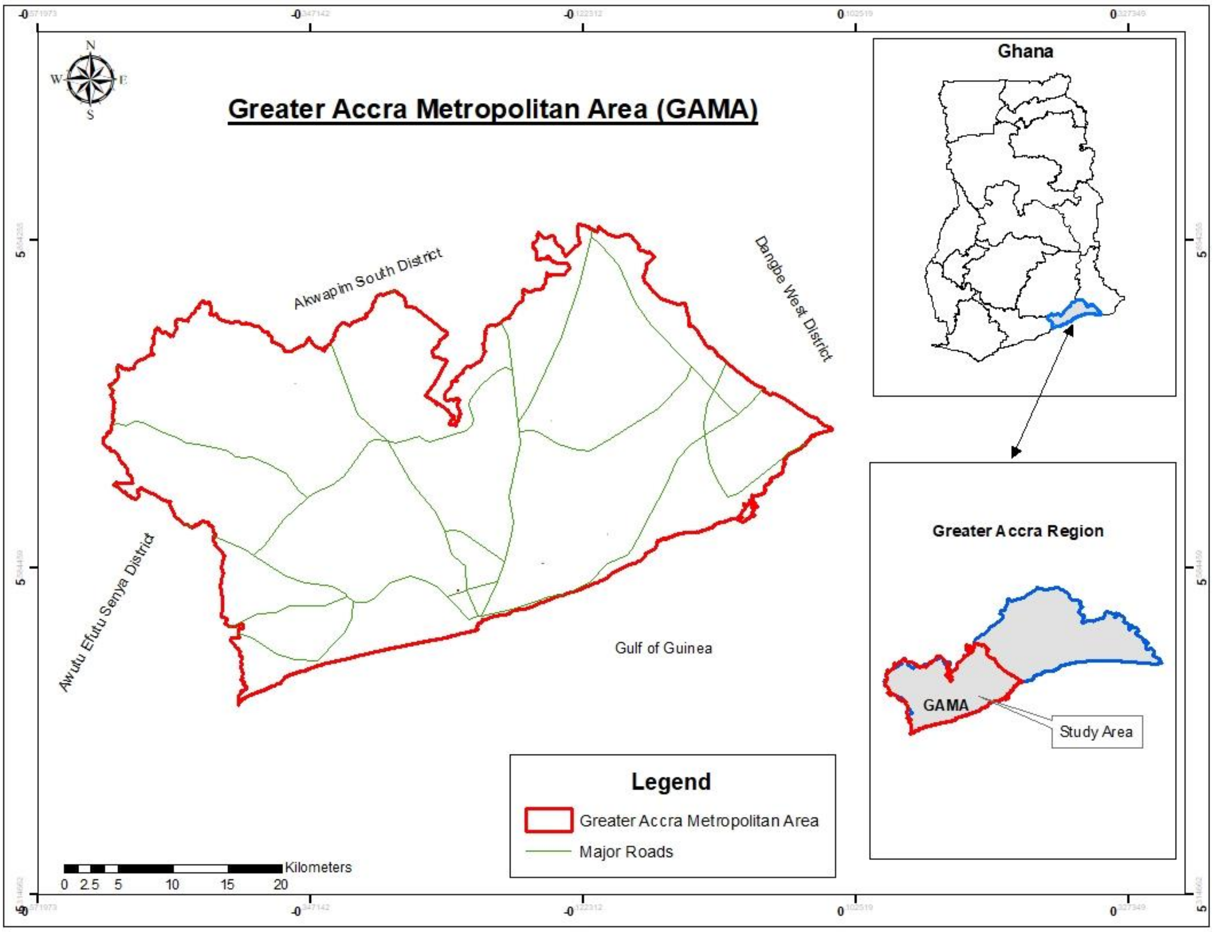


Figure 2: Map showing the Greater Accra Metropolitan Area

Figure 2 shows the Greater Accra Metropolitan Area which is located in the Greater Accra Region, Ghana. The red coloured section in Figure 2 shows the boundaries of the metropolitan area which covers an estimated 45% of the entire region. Major roads in the metropolitan is illustrated in green as seen in Figure 2.

The population of Greater Accra Metropolitan area according to the 2010 Population and Housing Census is 1,665, 086 representing 42% of the region's total population and estimated to currently have a total population of 2.27 million people (World Urbanization Prospects, 2021). The metropolis is entirely urban (100%). At the regional level, Greater Accra recorded the highest population growth rates of 3.1%. It is the most densely populated region with a density of approximately 1,236 persons per square kilometre in 2010 compared to 895.5 persons per square kilometre in 2000. The increase in population density implies more pressure on the existing social amenities, infrastructure and other resources in the country. (Ghana Statistical Service, 2014).

Accra serves as the Greater Accra region's economic and administrative hub. It is furthermore a centre for manufacturing, marketing, telecommunications, finance, insurance, and transportation. It was the fourth-most appealing foreign direct investment (FDI) destination in Africa in 2013 and at a compound annual growth rate of more than 50 percent – the fastest in Africa. The central business district of Accra contains the city's main banks and department stores, and an area known as the Ministries, where Ghana's government administration is concentrated. Economic activities in Accra include the financial and agricultural sectors, Atlantic fishing, and the manufacture of processed food, lumber, plywood, textiles, clothing, and chemicals. However, agricultural activities are not very common within the metropolis because it is predominantly urban.

3. METHODOLOGY

3.1 Sources of Data

Secondary data was primarily used in the study on the locations of fire stations in Greater Accra Metropolitan Area (GAMA). A visit was paid to the office of the GNFS in Cantonments- Accra, to collect data on the locations of fire service stations across GAMA, issues the fire service faces, the causes and effects of fire and emergency mitigating measures put in place by the department. They also talked about the various causes of fire as well as the various techniques that they apply in fighting fire incidents.

In addition, data on population density was derived from WorldPop based on official United Nations population estimates that have been prepared by the Population Division of the United Nations Secretariat (Department of Economic and Social Affairs Population Dynamics, 2019).

The dataset was produced based on the 2020 population census/projection-based estimates for 2020, building footprints provided by the Digitize Africa project of Ecopia Tech Corporation and Maxar Technologies (WorldPop, 2020) and gridded building patterns (Dooley et al. 2020). Also, relevant shapefiles within the GAMA was obtained from the Remote Sensing/GIS Lab, University of Ghana website for data analysis. Current road data in GAMA was accessed from Open Street Map in ArcPro.

3.2 Software used

The study used the following GIS software application tools to achieve the objectives outlined in the study. These included ArcGIS applications such as: ArcPro and ArcMap for data analysis and the generation of finished maps. ArcGIS applications enables the creation of geographic information that is captured and preserved as geodatabases, map documents, geoprocessing toolboxes, image files amongst others such as Open Street Map (ESRI, 2019).

3.3 Data Analysis

3.3.1 Spatial distribution of existing fire stations:

The data collated from GNFS on the locations of existing fire stations was structured in Excel. The location data in Excel in X, Y was imported into ArcMap and stored as a shapefile for analysis. To show the spatial distribution of existing fire stations in GAMA, the geo- locations of these stations were plotted and mapped out using ArcMap.

3.3.2 Service Area Coverage:

To determine the service coverage of existing fire stations, two spatial analysis tools were used, that is the buffer and the network analysis tool. For the buffer analysis, the Euclidean buffer tool was used. This can be described as a tool to measure distance on a two-dimensional Cartesian plane, where straight-line or Euclidean distances between two points on a flat surface are computed (ESRI, 2021). Euclidean buffers are the most frequent form of buffer and are useful when evaluating distances between features (Wu et al., 2019). Hence, the Euclidean buffer tool was used in the study from the data management geo-processing tools found in

ArcMap. The value of the buffer distance in linear units used in the study was in kilometers. The existing fire stations were therefore given an 8-kilometer radius to determine the maximum coverage area. The buffer radius was set to 8 kilometers because it is the maximum coverage area pegged for each fire station by international fire regulations standards (NFPA, 2021; OSHA, 2015).

Secondly, the network analysis tool was used to determine the coverage of existing fire stations through average time travel to fire incident scenes from existing fire stations. The network analyst tool models the movement of cars and trucks while developing solutions that minimize trip distance. Travel distance calculated adheres to one-way streets, avoids unlawful turns, and adheres to other car-specific restrictions. The network analysis tool can be found in the geo processing toolbox within an ArcGIS Online hosted data and analysis capabilities in ArcPro. This allowed the use of OpenStreetMap data to access road data (major and minor roads) and average traffic conditions in the Greater Accra Metropolitan Area. Road data is essential because, easy access to transport routes by fire service wagons is important in saving lives and properties within the shortest possible time when a fire outbreak occurs (Wilmoth, 2019).

For the purpose of this research, international fire safety regulations developed by the National Fire Protection Association (NFPA) was used. Suitable travel time according to the accepted codes was pegged at 5, 10 and 15 minute travel time from facility to fire incidences (NFPA, 2021). According to NFPA (2021), the optimum travel time from a fire facility to a fire incident scene to prevent a fire outbreak is 5 minutes while 15 minutes is the maximum amount of time to a fire incident scene. If a fire trucks arrives to a fire incident scene in more than 15 minutes travel time, there is a high possibility devastating consequences of the fire has already occurred (NFPA, 2021). Hence, to determine the service area coverage in this research average travel time from existing fire stations to fire incident cases was analysed in a 5-15minutes travel time within GAMA. The network analysis tool created buffers showing the service area covered of the overlaid point data of existing fire stations. The area covered according to estimated travel time was measured in kilometers square.

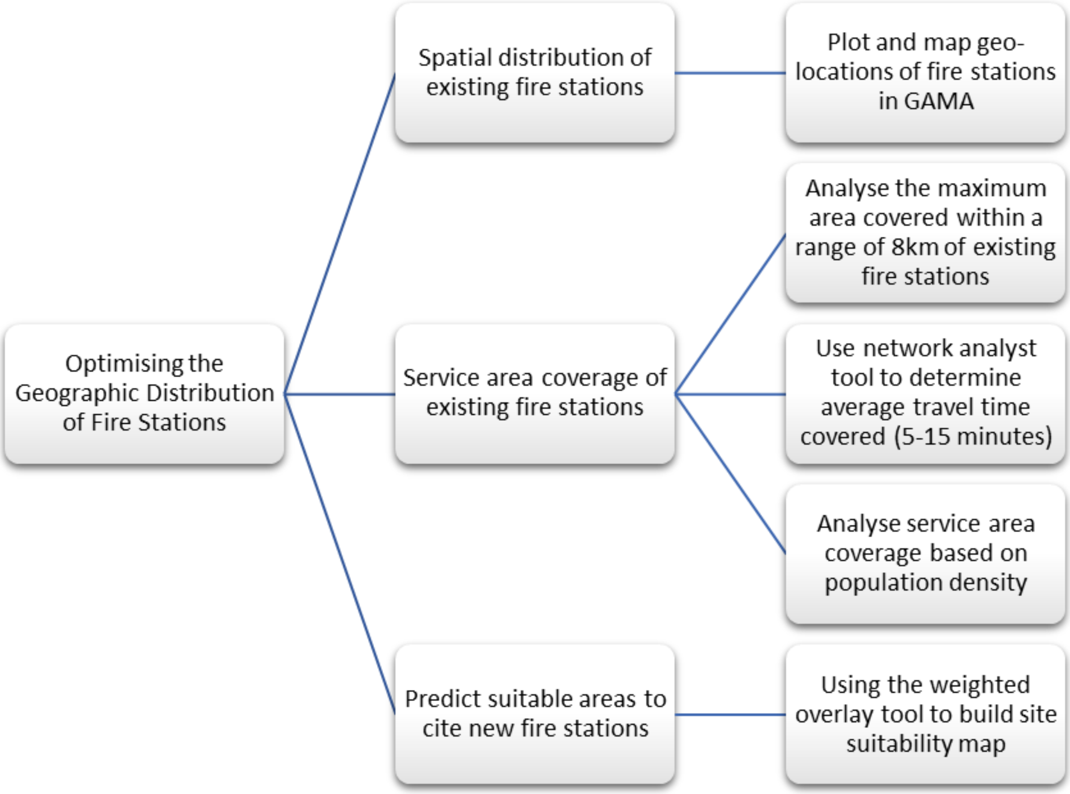
Lastly, the population density in 2020 for the Greater Accra Metropolitan Area was also analysed. This analysis was explored because on consultation with fire service personnel at the headquarters, high population density is a major criteria used in citing fire stations across the country. Thus, population data was overlaid on existing fire stations to determine areas densely populated areas that did not have a fire service station within the study area. This procedure was done and mapped out in ArcMap.

3.3.3 Predicting suitable areas for fire stations:

To predict suitable areas for citing new fire stations in GAMA, the weighted overlay tool in ArcMap was used. This was done by assigning equal weights summing up to 100 on the following criteria: densely populated areas, maximum service area coverage of 15 minutes and 8km travel distance from existing fire stations. Population density was reclassified from a scale of 9 to 1 to show level of importance. Highly dense areas were classified as 9 and as the population density decreased the scale reduced. The least dense areas were given a scale of 1. In addition, maximum travel covered by existing fire stations was also reclassified. Areas that fell in within 5- 15 minutes travel time and an 8km distance covered from existing fire stations was reclassified on a scale of 9 to 1, with the farthest area given a scale of 9 to the closest area given a scale of 1. The weighted overlay tool was then used on the reclassified raster datasets to determine the most and less suitable areas to cite new fire stations in GAMA. Thus, by employing ArcGIS tools functions such as spatial analysis module and network analysis module the geographic distributions of fire stations was explored and analysed.

3.4 Summary of Methods Used

The major goal, as shown in figure 3, is to optimize the geographic distribution of fire stations, which can be accomplished by achieving three sub-goals.



That is, to map out the spatial distribution of existing fire stations, determine the service area coverage of these stations and predict suitable areas for new fire stations. The first sub-goal looks at analyzing the spatial distribution of existing fire stations within the Greater Accra Metropolitan Area. This was done by collating the location data of existing fire service stations as seen in figure 3. The second sub-goal is to determine the service coverage area of existing fire stations. This is further broken down into three categories: buffer analysis, network analysis and population density analysis to determine the service covered by existing fire stations in figure 3. This was done to identify the areas that are covered and areas not covered with the existing fire stations in GAMA. In figure 3, the third sub- goal to achieve the main goal of the research is to predict suitable areas for citing new fire stations. This goal was achieved by employing the use of the weighted overlay tool to build suitability maps. In summary, to efficiently optimize the distribution of fire stations in GAMA, the horizontal hierarchical flowchart as seen in figure 3 was used as a guide in the research.

4. RESULTS

4.1 Spatial Distribution of Fire Stations in GAMA

To have a visual representation of the spatial distribution of fire stations across GAMA, the geolocations of these fire stations were plotted in ArcMap as indicated in Figure 4.

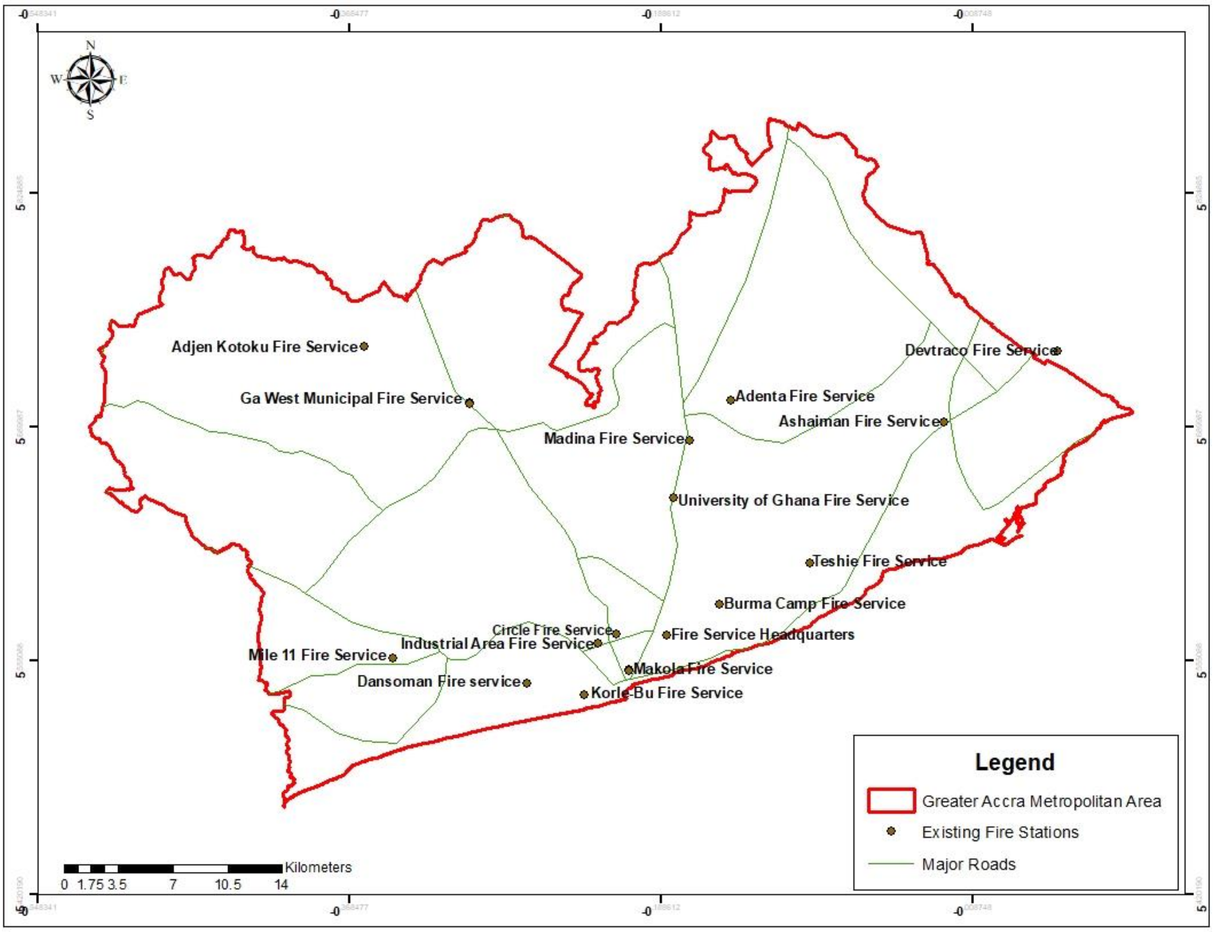


Figure 4: Spatial Distribution of Fire Stations in GAMA

Figure 4 shows that the fire stations in GAMA are unevenly distributed. Many of the fire stations are located in the southern portion of the metropolitan area, whereas the southern and eastern parts of the study area have very few. The fire stations in figure 4 are denoted by red points. The uneven distribution of fire stations in the metropolos according to fire service personnel at GNFS is attributed to the high population density in these regions at the time funding for new fire stations were granted. However, due to the impacts of urbanization and urban expansion, population has risen over time in all districts of the Greater Accra Metropolitan Area hence a need to cite new fire service stations.

4.2 Service Areas of Existing Fire Stations

Fire service agencies including Ghana abide by international standards for fire safety and management (NFPA, 2021). One of such international standards is the NFPA standard codes which state measures to ensure sufficient fire station placements in an area. Thus, a fire station should be situated so that every portion of the jurisdiction is within 5 miles (8 kilometers) of a fire station (NFPA, 2021). It is stipulated that anything beyond 8km jurisdiction of a fire station is considered as an area with no recognized fire protection. Ideally, within 1.5 miles (2.5 kilometers) of a built-up urban region, should be the fire protection area assigned to a fire service (NFPA, 2021; Chaudhary et al., 2016). Thus, buffer analysis was done around existing fire stations in GAMA to determine the extent of coverage each fire station has within an 8km radius. This is done to determine areas that are without fire protection. The reason for the buffer of 8km is because fire safety standards stipulate that the maximum areal coverage of a fire service station should be 8km. That is, for every 8km, a fire service station should exist in a region (NFPA, 2021; Chaudhary et al., 2016).

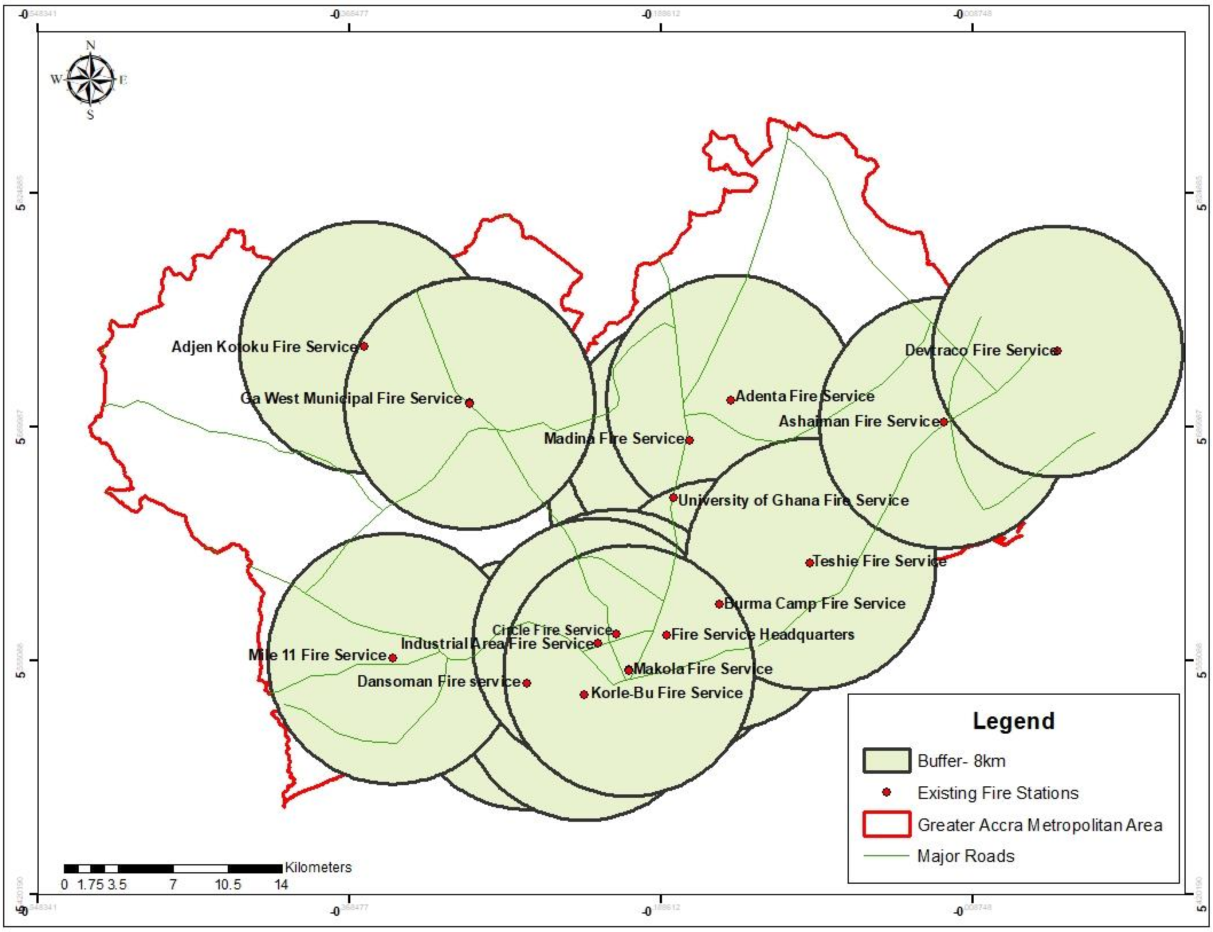


Figure 5: Buffer Analysis of 8km of Existing Fire Stations in GAMA

In figure 5, the green circled areas indicate a coverage of 8 kilometers service area of existing fire service stations. A visual analysis of the map shows that some areas in GAMA are not within range of coverage of existing fire service stations in GAMA.

To further buttress the above fore-mentioned points, another way to measure service coverage area is by measuring fire response time of fire rescue vehicles to fire incident cases. This is significant because fires are classified time sensitive emergencies and life threatening, which means that a delay in response by fire emergency vehicles will result in loss of life or properties (Yang et al., 2020). According to the National Fire Protection Association (NFPA) Standard 1710, it defines an 80 second "turnout time" and 240 second "travel time" benchmark time target for not less than 90% of dispatched fire occurrences (NFPA, 2021). This implies that fire service stations are to respond to every fire incident within an optimal time of 5 minutes to reduce/prevent the damage to lives and property. The optimum travel time is calculated using the network analysis tool in ArcPro to show average travel time of 5 minutes of existing fire stations to determine the areal coverage. The analysis done combined average traffic conditions with existing road networks sourced from Open Street map in the metropolitan area as seen in Figure 6 to determine the average travel time in 3 intervals of 5, 10 and 15 minutes.

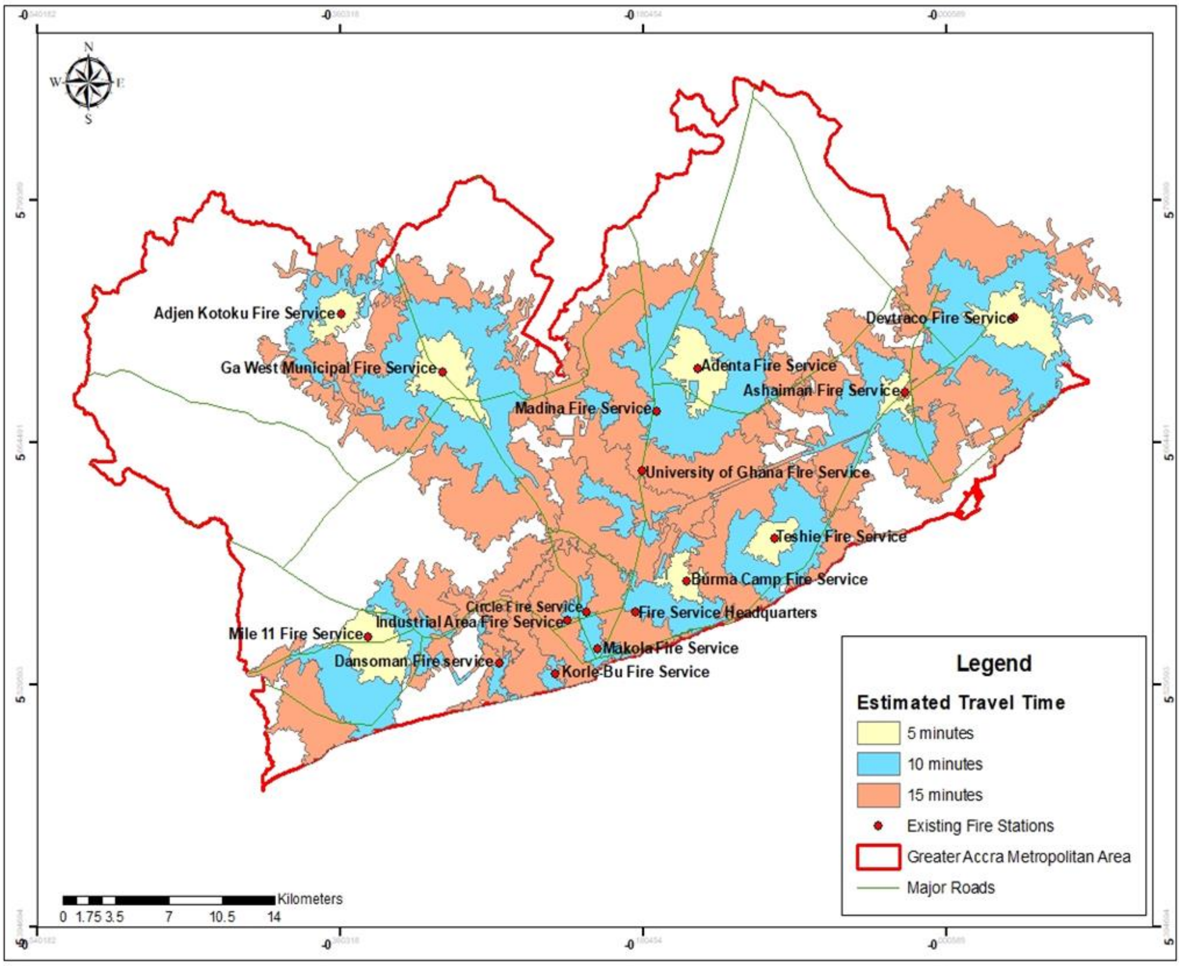


Figure 6: Estimated Service Area Coverage of Existing Fire Stations in GAMA within 5-15 minutes Travel Time

Figure 6 shows the estimated service area of existing fire service stations between a 5 to 15 minute travel times to reported fire incident scenes. The travel time takes into account the average time for a fire engine to get from a fire station to an incident location (wheel start to wheel stop) (Yang et al., 2020; Chaudhary et al., 2016). The traveling time was analysed through overlaying the location of existing fire stations and setting travel time to 5 minutes according to NFPA Standard Codes from the fire station to the incident scene through the most efficient travel route (NFPA, 2021). From figure 6, the yellow regions represent areas of coverage within a 5 minute travel time and the blue within a 10 minute report time. It should be noted that at a 5 minute travel time the average area covered within GAMA is 8 kilometers and for a 10 minute travel time the average area covered is 2.8 kilometers. A 15 minute coverage analysis was also done and this is depicted in orange with an average coverage of 4.74 kilometers. From Figure 6, one can identify that although fire stations are evenly distributed in Ablekuma (North, Central and South), Ashiedu Keteke, Okaikoi South and Korle Klottey Municipal, the average travel time with existing road networks is 10 minutes. This is due to high traffic congestion within these areas (Musah et al., 2020).

Furthermore, data on population density within the research region in 2020 was also mapped out to better understand the service areas served by current fire stations. This was done to determine the link between the demographics in an area to existing fire service stations. Population distribution is important in citing fire stations because a high number of people within a given area means a more dense building coverage (Nyimbili et al., 2018). This implies that, highly populated regions typically have dwellings on relatively small areas and near to one other, increasing the likelihood of fires and the speed with which they spread. Thus it is important to respond quickly to these regions and ensure the supply of fire department services to them in order to avoid unanticipated large damages. In an interview with fire service personnel, they however stated that with limited resources available to fire service, high populated dense areas is a major criteria used in citing fire service stations across the country.

For the analysis, population density figures were taken from United Nations population estimates (WorldPop, 2020). The dataset contains the estimated number of persons discovered per grid cell 100 meters from the equator. This means that it displays the estimated population in a particular region at a 1km radius grid cell. Figure 7 therefore depicts a graphic distribution of estimated population density in GAMA in 2020 overlaid on existing fire service stations.

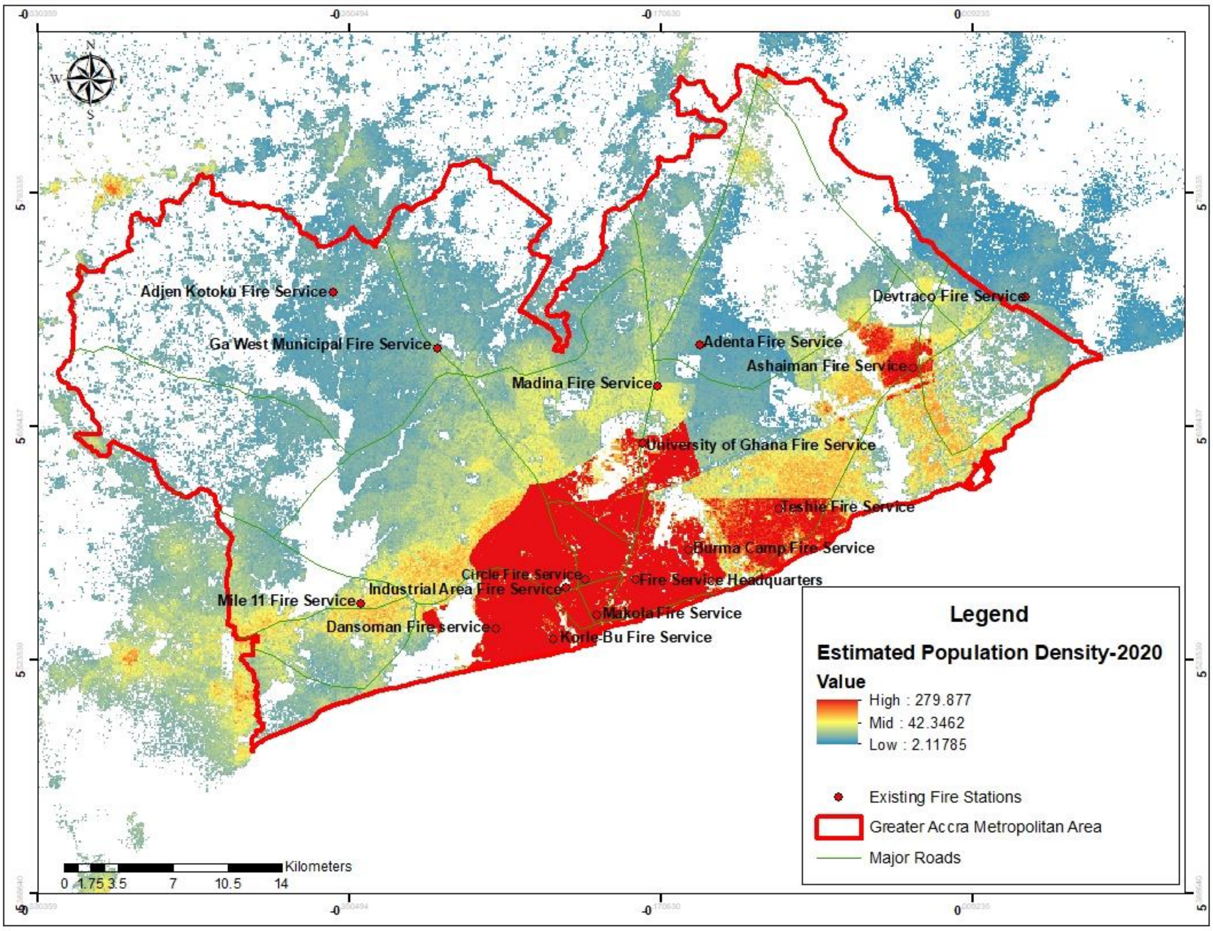


Figure 7: Estimated Population Density in 2020 within GAMA

The population density is shown in graded hues in figure 7. High-density regions are represented in red, whereas low-density areas are depicted in blue. For areas in red, it implies that at every 1km, 280 people are likely to reside in these areas. Mid-dense regions are shown in yellow, while low-density areas are shown in blue, with an average of 2 persons within a 1km radius in the area of study. Regions represented in white show areas that have been mapped as unsettled based in building footprints provided by the Digitize Africa initiative (WorldPop, 2020). Figure 7 buttress the fore-mentioned point on the citing of fire stations in highly populated areas.

4.3 Predicting areas suitable for citing new fire stations

To predict suitable areas to cite new fire stations, site suitability analysis was done. The analysis incorporated the population density of the area and service area coverage of existing fire stations. This was done to determine areas that are vulnerable in the event of a fire outbreak as seen in Figure 8.

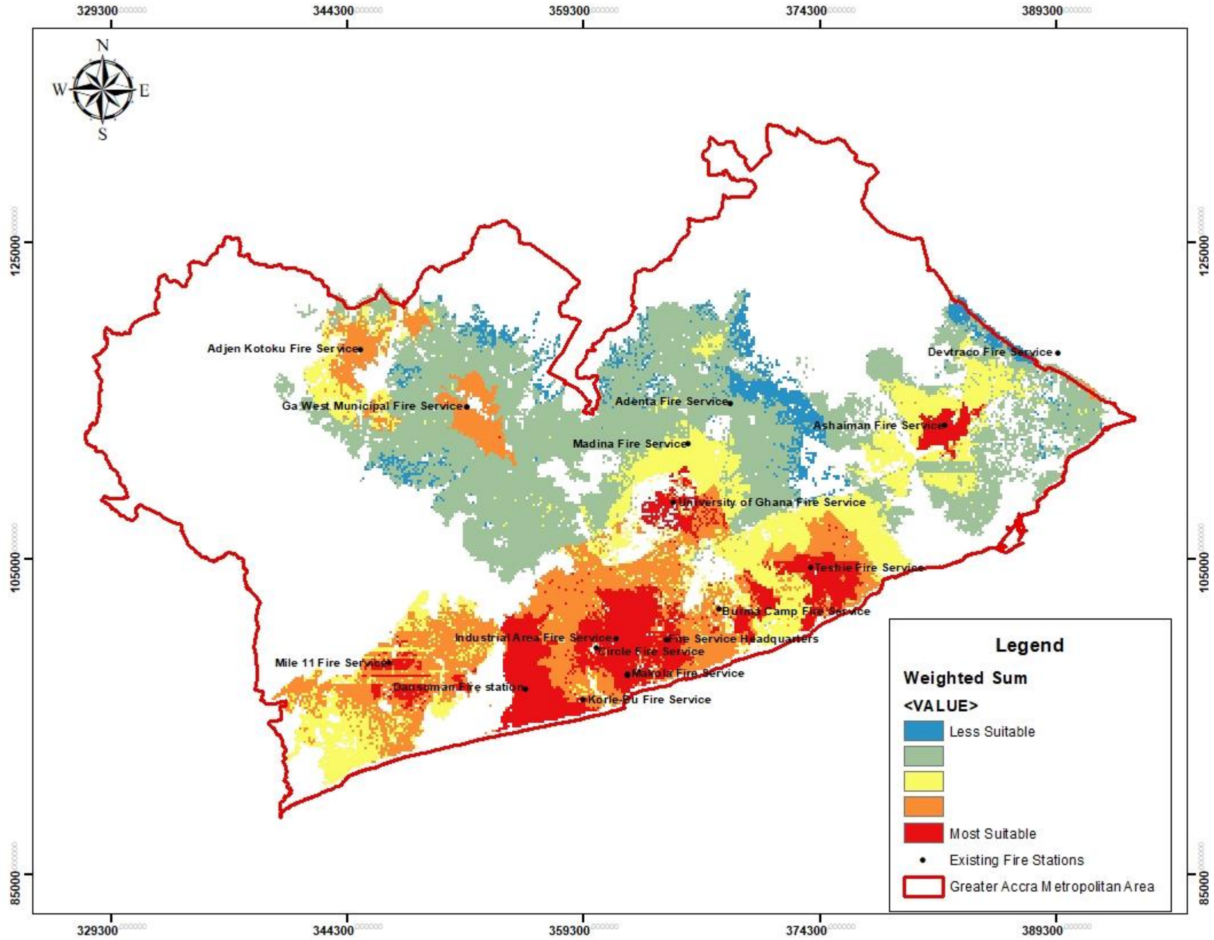


Figure 8: Suitability map for citing new fire stations in GAMA

From the analysis done in Figure 8, the graduated colour from red to blue, pinpoint areas that are suitable for citing fire stations in GAMA from the most to the least. Areas depicted in red are the most suitable region to cite a fire service station. In figure 8, one can identify that the areas most suitable for a fire service station have an existing fire station. In addition, areas depicted in orange is the second most suitable region to cite a fire station. However, from figure

8, one can identify that most parts shown in orange suitable for a fire station, do not have one. Pockets of green areas in figure 8 also highlight the third most suitable area to cite a fire service station within the metropolis with blue areas the least suitable area. Areas depicted in white are negligible areas in the model due to the low population density within such areas. Thus, the multi criteria results as seen in figure 8, easily identifies suitable areas to cite new fire service stations to ensure maximum coverage with the use of geospatial technologies. This tool can be used by relevant stakeholders in fire disaster management and prevention in the Greater Accra Metropolitan Area to meet the growing demands of the urban environment.

5. CONCLUSIONS

The main goal of this study was to explore the use of geospatial tools in optimizing the geographic distribution of fire stations in the Greater Accra Metropolitan Area. This was categorized into three objectives by: analyzing the spatial distribution of existing fire stations, determining the service coverage of existing fire stations and predict the locations of new fire stations in areas that do not fall in the coverage area of the existing fire stations. To achieve the objective of the study, geo-locations of existing fire stations were plotted in ArcMap to show the spatial distribution of existing fire service stations. In addition, the service area covered by existing fire stations was also explored by using the network analysis tool in ArcPro to determine the maximum expected travel time of 15 minutes (NFPA, 2021) to fire incident scenes. The tool employed the use of road and average traffic conditions data within the metropolis derived from OpenStreetMap. Buffer analysis was also explored to determine the maximum area coverage of 8km (NFPA, 2021) from existing fire stations based on fire regulation standards. Population density was also mapped out in the study, to show populated areas that had an existing fire service and those that did not have one.

Furthermore, the research explored the spatial distribution of fire stations, service area coverage of existing fire stations and population density as a criteria to develop a site suitability map to predict areas suitable for new fire service stations within GAMA. Each criteria was given equal weights to create a suitability map using the weighted overlay tool in ArcMap.

In conclusion, the paper explains the concept behind an effective emergency management system that makes use of GIS technologies. Though an emergency never arrives with advance notice, we may use this location and GIS integrated mapping system to analyze the geographical position of current fire stations, analyze it, and forecast where new fire stations might be located to help reduce risks during fire outbreaks. This will allow for the dispatch of emergency units to fire incidents in GAMA in the shortest amount of time. The objective of this study was to develop a map that depicted the geographic distribution of fire stations and their coverage area, while also forecasting appropriate places to cite additional fire service stations in order to decrease the catastrophic consequences of fire outbreaks in the study area.

6. RECOMMENDATIONS

The analysis of spatial data and the findings discovered in the study has encouraged the formulation of recommendations by the researcher, directed at policy makers together with researchers in future to conduct a more elaborate research on optimising the geographic locations of fire stations to ensure maximum coverage and save lives and property. In order to ensure that the spread in urban development do not result ineffective emergency management, the following recommendations are proposed:

- Policy makers should focus on risk and mitigation measures in the growing urban environment in GAMA to prevent the loss of lives and properties. This includes building adequate emergency facilities to meet the growing demands of the urban environment
- Government sectors especially the Ministry of Interior which mans the Ghana National Fire Service and relevant stakeholders should allocate the much needed resources to rejuvenate fire response measures, purchase firefighting equipment, train skilled personnel and introduce GIS into fire response system in the country

- Educate public stakeholders for safety in Ghana, the high advantages of using geospatial technology for effective emergency management system.
- GIS technologies is growing in the developed regions and it has a lot of advantages. Therefore, it is crucial that GIS applications are incorporated into the education syllabus to teach young people how they can use these tools to promote efficiency. Through these more innovative ways can be developed to bring Ghana a step closer to the advancement in modern technology.
- Elaborate research into the use of GIS based applications in emergency situations should be made in order to develop more innovative ways to save lives in the shortest possible time.
- This study can also be employed in the optimum location of emergency facilities such as the National Ambulance Service, NADMO and the Ghana Police Service.

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