Application of GIS-based Multi-Criteria Decision-Making Analysis for the Selection of Locations of Fire Stations

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Abstract

The growth and development of the city of Ilorin over the years, as warranted the proper planning of the city, to attain urban growth and development sustainability. The purpose of the study is to use geographic information system (GIS) based multi-criteria decision-making analysis (GIS-MCDA) to select suitable locations for siting fire stations in the metropolis. This study utilized analytical hierarchical process (AHP) analysis in the GIS environment to select areas most suitable for siting fire stations within the region. Overall, 9 criteria factors such as population density, proximity to roads, slope, proximity to built-up areas, proximity to schools, proximity to hospitals, proximity to petrol stations, proximity to police stations, and including proximity to the existing fire stations were formulated based on the study area, and through comprehensive literature review. These criteria were weighted using AHP method, and integrated using the weighted overlay tool to produce the suitability map of the proposed locations for the fire stations. The resulting findings identifies 11 sites that are considered suitable for situating fire stations, with 5 amongst the 11 most suitable for siting new fire station locations. Also, the result of the study can assist policy makers in determining the most suitable locations of fire stations in cities. Follow up studies will focus on combining AHP with other techniques like Fuzzy logic and spatial modelling methods to facilitate the modification of the proposed method and its applications to the site selection processes.

Keywords: Location, AHP, Fire stations,criteria, Ilorin Kwara State, Nigeria.

INTRODUCTION

Fire disaster emergency response systems require the proper locations of fire service stations concerning the social and environmental components such as population growth, urbanization, and industrialization upon which fire accidents are categorized as domestic or industrial fires (Waheed, 2014; Addai *et al*., 2016; Granda and Ferreira, 2018). In order for fire accidents to be classified as either residential or industrial fires, fire disaster emergency response systems require the right placement of fire service stations in relation to social and environmental factors including population expansion, urbanization, and industrialization (Waheed, 2014; Addai *et al*., 2016; Granda and Ferreira, 2018).

The following steps are the framework of a site selection decision: (1) deciding the standards by which the alternatives are assessed: (2) Outlining pertinent criteria for the decision-making process; (3) creating multi-criteria site selection alternatives for the decision-making process (4) Considering the options and making the ultimate site selection decision (Erturgal I. and Karakasoglu N., 2008).

Over the past three decades, the metropolis of Ilorin has experienced significant urbanization and population increase. the National Population Commission's data. The Ilorin metropolis has witnessed rapid growth in population and urbanization over the last three decades. Records from the National Population Commission put the population of Ilorin as 532,088 in 1991 and is projected to be 3,518,771 by 2020 (Ibrahim *et al* 2020). This indicates that the risk of fire disaster occurrence in Ilorin could increase.

The most appropriate position among alternatives can be found using a variety of techniques and problem categories. However, a lot of these placement decisions are made through straightforward analysis based on instinct, experience, or even predisposition. In addition to straightforward approaches, more complex ones that involve statistical and mathematical tools have also been suggested. Geographic Information Systems (GIS) can handle both spatial and non-spatial data thanks to information technology, which gives them specialized responsibilities in data administration and integration, data query and analysis, and data visualization (Cheng et. al., 2007).

For the fire service department to meet up the developing challenges of effective and efficient disaster management and response, they require adopting technology to assist them in identifying an emergency; determining the quickest and shortest route to an emergency site; providing additional fire station locations and fire service coverage modeling (Pondi, 2015). A system called the Geographic Information System (GIS) has been developed by researchers to help extract the physical characteristics of the earth's surface to manage, analyze and display the geographic data (Wang, 2019).

GIS allows making analysis that determines the location of facilities on main roads, residential areas, important buildings, and so on. An attractiveness matrix gives total values of location analysis. In addition, GIS allows network analysis which helps to determine service areas (coverage). Using network edges and junctions, for instance, you may find out where a vehicle can drive in the allotted amount of time if you know the speed rates of the roadways. Urban fire is one of the most prevalent issues, affecting both developed and developing nations (Nuisance, 2010).

In developing countries, a very large amount of property and lives are unfortunately lost through fire annually. For instance, in the year 2006, the Ghana National Fire Service (GNFS) recorded one thousand nine hundred and eight-six fire outbreaks that destroyed properties worth thousands of Ghana cedes (Aziz, 2007). Since fire outbreaks frequently make the country's poverty level worse, there is a significant economic cost to the government.

Therefore, it's crucial to provide emergency response services, particularly in the case of fire disasters, to prevent the nation from losing its limited resources. This led to the establishment of the GNFS (Ghana National Fire Service) in 1963 to control fire outbreaks in the country and, since its inception, GNFS has embarked on programs and activities to educate the public on fire safety and prevention measures while fire stations were established in the major cities. These stations were equipped with modern techniques to preserve lives, property, and natural resources for the sustainable development of the people of Ghana. Even now, despite the use of contemporary fire control and suppression methods, flames still cause property damage, particularly in Kumasi's Central Business District (CBD), where the management of urban fires requires a regionally effective planning and response system.

Similarly, (Chevalier *et al*, 2012) used an integrated GIS approach to locate fire stations in Belgium. The system was designed for the effective management of fire station locations and allocations. In their analysis, a multi-scale GIS which includes a risk modeling approach was used to determine the optimal location and allocation model taking into account the queuing as well as staffing problems

Study Area

Ilorin, the Kwara state capital, is located within Latitude 8° 29' 43"N & 8° 30' 50"N and Longitude ° 31' 48"E & 4° 35' 40"E (Figure 1). Ilorin metropolis is comprised of three local government areas, namely, Ilorin West, Ilorin East, and Ilorin south. Ilorin is highly populated with people from different tribes including Yoruba, Igbo, Hausa, and Fulani. The two main religions practiced in Ilorin are Islam and Christianity. The city is relatively developed, hosting several industrial establishments including Olam International (Africa's biggest Cashew processing plant), Dangote flour mills, Tuyil Pharmaceutical, KAMWIL, Chellaran motorcycle assembly plant (Saad, 2013). Ilorin is also home to several tertiary institutions like the University of Ilorin, Kwara State University, Al-Hikmah University, Kwara Polytechnics, College of Education, and many others. The major roads in Ilorin are very good, and they provide access to several small and medium-scale businesses including; Banks, Hotels, Restaurants, markets, and supermarkets. The service area considered in this study covers Ilorin south, Ilorin east, and west local government areas. The three areas sum up the Ilorin Metropolitan area.

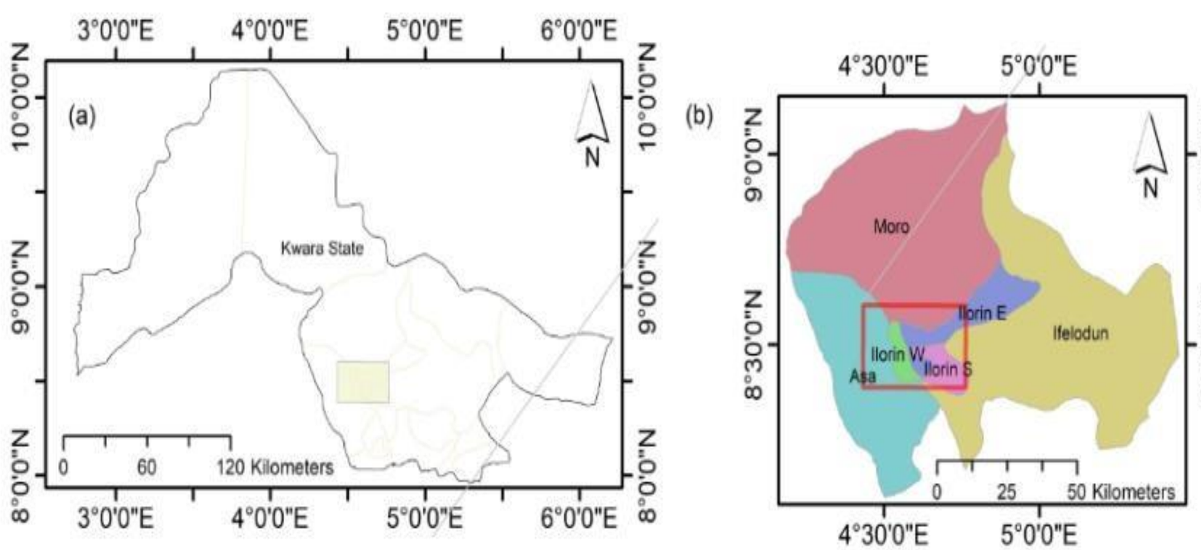

Figure 1: Location of the study

METHODOLOGY

The main objective of this study is to suggest new fire station locations in Ilorin Metropolis, to help the fire services personnel of the state to achieve better coverage of the study area. In the context of the set objective, the following steps are followed (see figure 1)

The objective of this study is to identify suitable locations for new fire stations. To achieve this, potential criteria for finding new fire station locations were considered. Data was collected, prepared, and transferred to a GIS environment. The criteria were then formulated into raster datasets, which were classified and reclassified. A preference matrix was established by assigning preference values to relevant criteria using the pairwise comparison feature of AHP. Criteria priorities/weights values were calculated by synthesizing priorities and calculating overall composite weights. The result raster suitability map of potential fire stations was obtained using weighted overlay techniques. Based on the analysis, new fire station locations are to be proposed/suggested.

Setting up the Criteria

Nine criteria have been considered for this study based on a previous study by (Erden, 2010). The important criteria considered for the study are distances between fire stations, population density, and the road network of the study area. Since the Ilorin metropolis is a city with quite high population densities, the population density is taken as the first criterion for consideration. Road associability is another important criterion that will be considered for fire station location and its activities. Ilorin metropolis has heavy industrial activities happenings; therefore, it has lots of hazardous material facilities that can be affected by fire outbreaks. Also, the terrain of a fire station location is of great importance to the location of a fire station facility. Therefore, the slope is another criterion considered for the study. The above-mentioned criteria can be abbreviated as population density (PD), Proximity to the existing fire station (PEF), Proximity to main roads (PMR), Proximity to Hazardous points (PHP), Proximity to Emergency response points (PEP) Land use land cover (LULC).

After the criteria have been considered, the criteria priorities/weights values were calculated by using the synthesis of priorities of AHP. To obtain a resulting map of the study, the weighted overlay technique was used. The weighted overlay technique is a technique for applying a common measurement scale of values to diverse and dissimilar inputs to create an integrated analysis. In order to determine the best places for the pre-existing collection of interacting elements, the technique entails creating criteria maps and superimposing them on top of one another to create a composite configuration.

Data preparation and analysis

A case study employing the Ilorin metropolis geodatabase in the GIS environment, using the ArcGIS 10.7 program, was conducted to demonstrate the selection of fire station locations. the core ArcGIS Desktop program tools for designing and constructing geographic geodatabases, producing geographic analyses, and making maps.

first step was to model the criteria set down for the study by producing a map of the Euclidean distances of the proximity to fire existing fire stations, proximity to hazardous prone points, proximity to emergency points, and also produce the map of the decision criteria such as the population density, the slope, the road network and the land use land cover (LULC) of the study area. The criterion map of the Euclidean distances was reclassified to enable the weighted overlay analysis to go smoothly. Next, the AHP pairwise comparison was done using the AHP calculator, by giving each of the criteria a certain preference according to their level of importance. The classified distances with the values assigned, along with the decision criterion were weighted and overlaid to produce the suitability map of the study area to enable the best suitable locations for new fire stations.

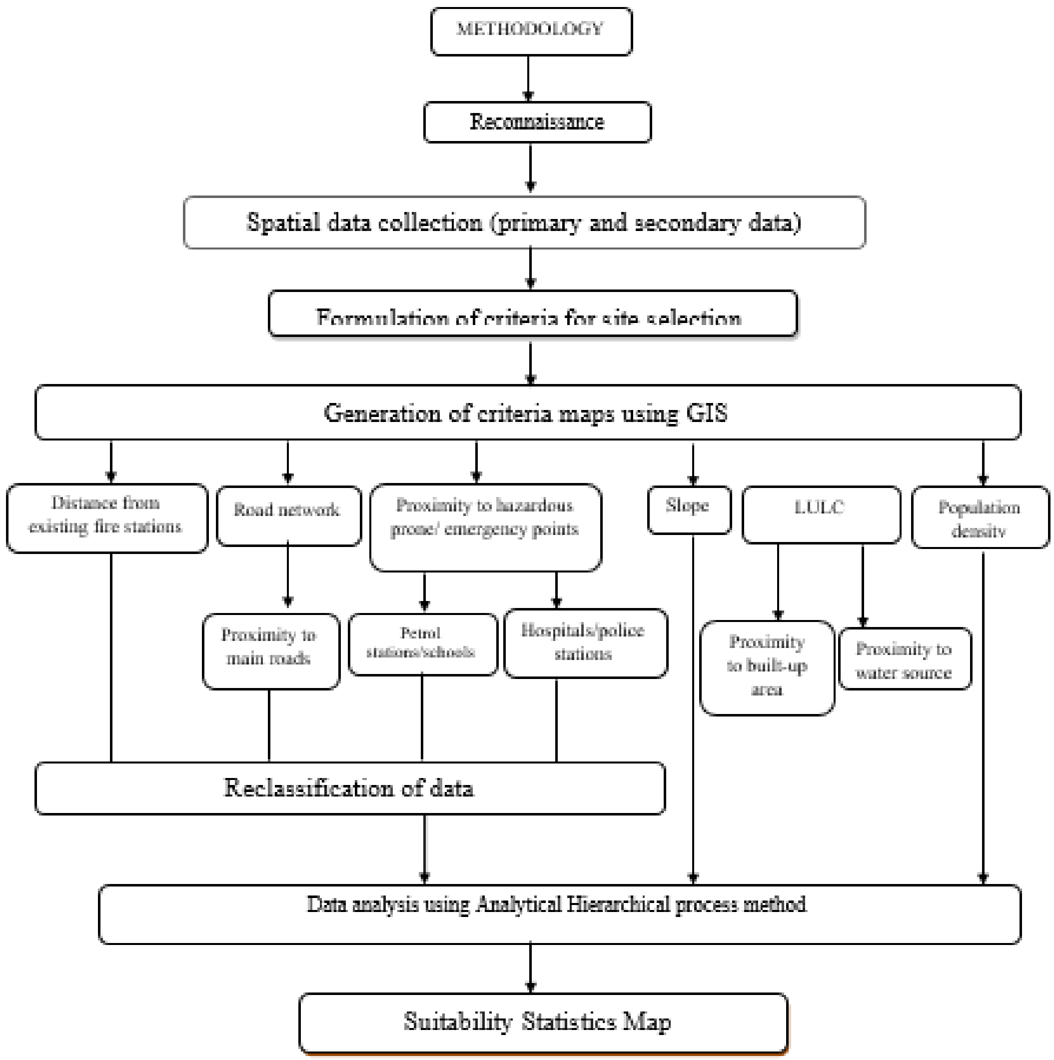

Figure 1 show the flow chart for Methodology used in achieving the objectives of this research work

Suitability map

The suitability of fire service station sites was generated through the weighted summation of different criteria layers using the ArcGIS 10.7 Raster Algebra tool (weighted overlay tool). The Weight of different criteria is shown in *table 3*. For proximity to the water source and built-up areas, they were excluded because they are contained in the Boolean layer of the land use and land cover criterion. The level of importance was defined in the weighted overlay analysis giving the top priority to proximity to the built-up area followed by proximity to the water source, vegetation, and open land, respectively.

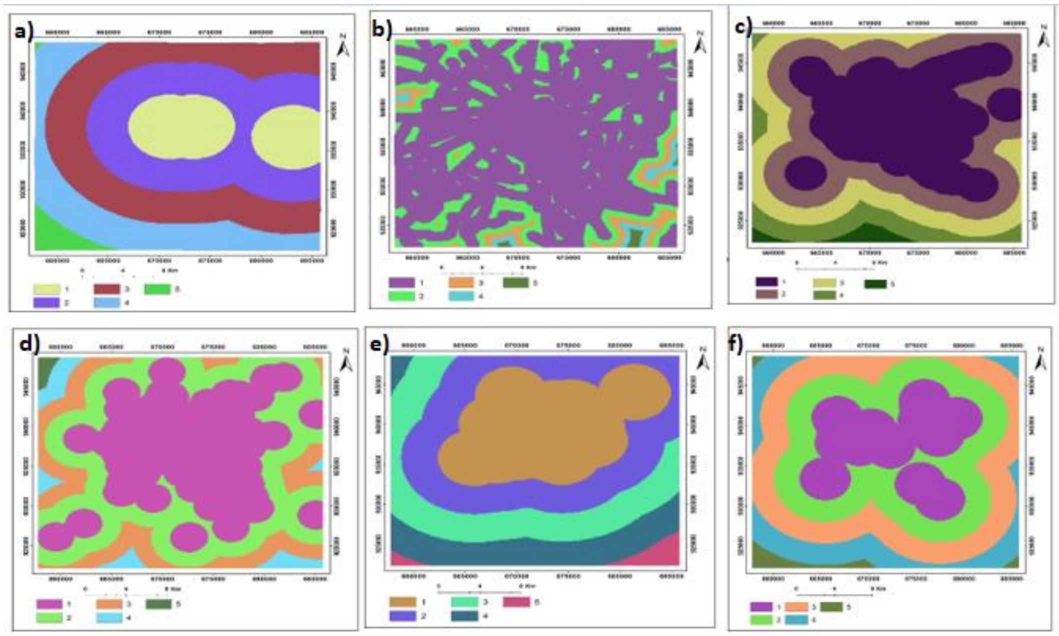

Figure 3. Maps showing Reclassified (a) proximity to existing fire stations (b) road network (c) proximity to petrol stations (d) proximity to schools (e) proximity to hospitals (f) proximity to police stations in the study area.

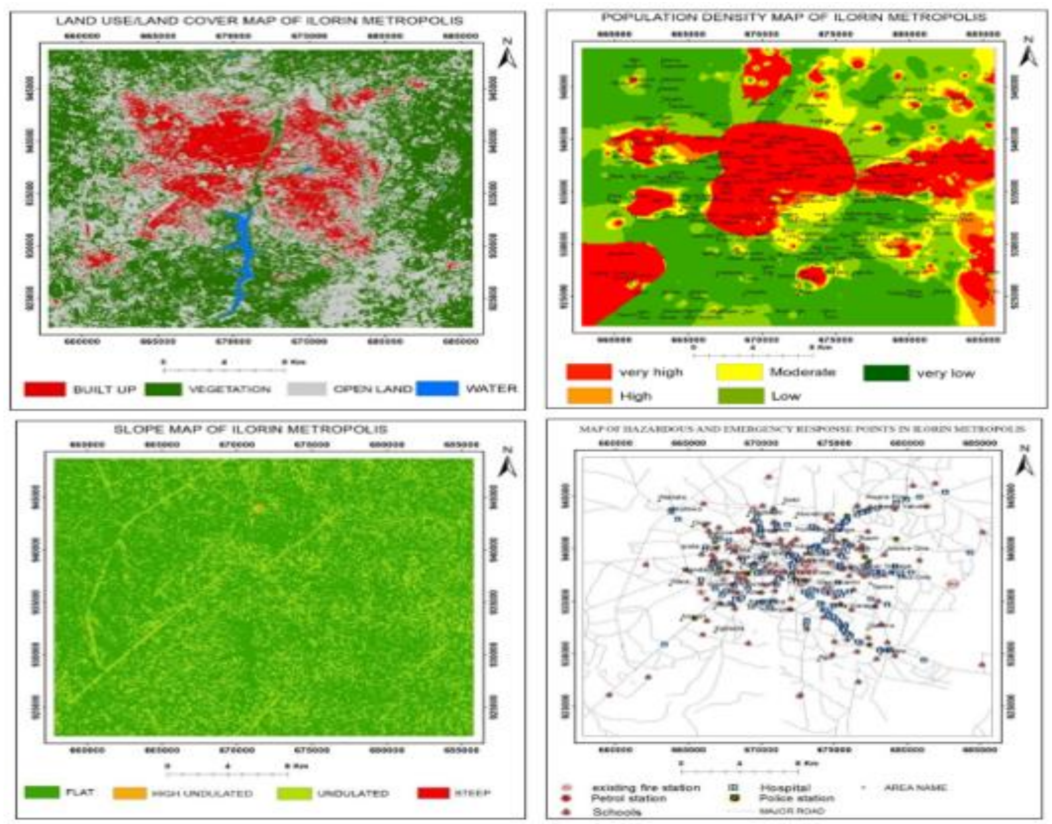

Figure 4. Maps showing (a) LULC (b) population density (c) slope and (d) hazardous & emergency points.

Table 1. Priorities based on Pairwise Comparison

S/N	Criterion	Rank	Priority	(+)	(-)
1	Population density	1	22.5%	18.3%	18.3%
2	Distance from existing fire stations	2	15.0%	6.9%	6.9%
3	LULC	4	13.7%	5.6%	5.6%
4	Slope	6	10.8%	4.5%	4.5%
5	Proximity to petrol stations	5	13.6%	3.1%	3.1%
6	Proximity to major roads	3	14.2%	6.9%	6.9%
7	Proximity to schools	7	3.8%	2.5%	2.5%
8	Proximity to police stations	9	3.1%	0.8%	0.8%
9	Proximity to hospitals	8	3.3%	0.8%	0.8%

Table 2. Weights for the Criteria based on Pairwise comparisons

		Population	*Dist to fire stn*	*Dist frm major road*	*LULC*	*Dist to petr stn*	*Slope*	*Dist to sch*	*Dist to hosp.*	*Dist to polc stn*
		1	2	3	4	5	6	7	8	9
Population	1	1	2.00	1.00	1.00	1.00	5.00	1.00	5.00	5.00
Dist to fire stn	2	0.50	1	2.00	1.00	1.00	7.00	1.00	3.00	3.00
Dist frm major road	3	1.00	0.50	1	1.00	1.00	5.00	2.00	5.00	
LULC	4	0.14	1.00	1.00	1	1.00	1.00	1.00	5.00	5.00
Dist to petr stn	5	1.00	1.00	1.00	1.00	1	3.00	1.00	5.00	5.00
Slope	6	0.20	0.14	0.20	1.00	0.33	1	0.14	1.00	1.00
Dist to sch	7	1.00	1.00	0.50	1.00	1.00	7.00	1	3.00	5.00
Dist to hosp	8	0.20	0.33	0.20	0.20	0.20	1.00	0.33	1	1.00
Dist to polc stn	9	0.20	0.33	0.20	0.20	0.20	1.00	0.20	1.00	1

Table 3. criteria priority/weight vector

S/N	Criterion	Derived Weights	S/N	Criterion	Derived Weights
1	Population density	0.225	6	Proximity to major roads	0.142
2	Proximity to fire stations	0.150	7	Proximity to schools	0.038
3	LULC	0.137	8	Proximity to hospitals	0.033
4	Slope	0.108	9	Proximity to police stations	0.031
5	Proximity to petrol stations	0.136		Total	1.00

RESULTS AND DISCUSSION

After class values are assigned to each criterion to produce the map layers, the criterion map layers were overlaid weighted overlay technique using the criteria priority/weight vector results in the GIS environment. A suitability map for the determination of new fire station locations was obtained after all the processes and procedures were achieved. Existing and new suggested fire stations are showed in the figure below.

In this study, the existing 2 fire stations are considered in the decision making and additional 11 fire stations are suggested in the study area. The purpose of this study was to find the optimum site for the new fire station in the study area based on the sound criteria stipulated and the suggested stations will provide better coverage of the study area. Therefore, the study identifies station number 2,3,5,6,9,10,11 as seen in (Figure 6) as the best location to site new fire stations out of all the proposed locations. This is based on solid criteria such as population, proximity to existing fire stations, proximity to hazardous material facilities, and proximity to the road network.

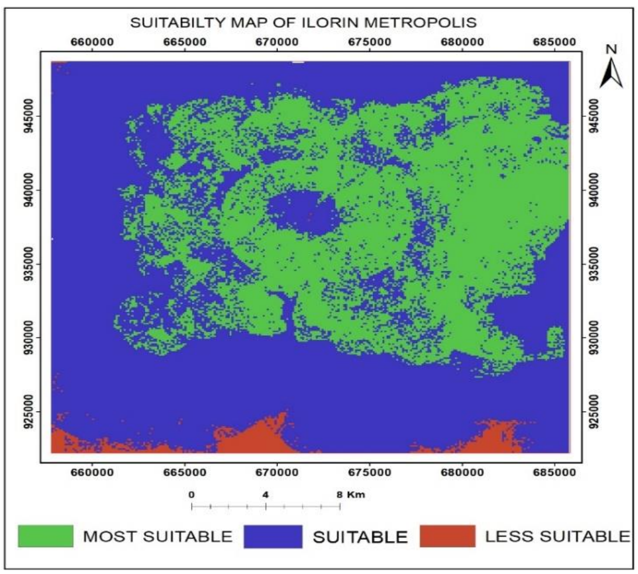

Figure 5. Suitability Map

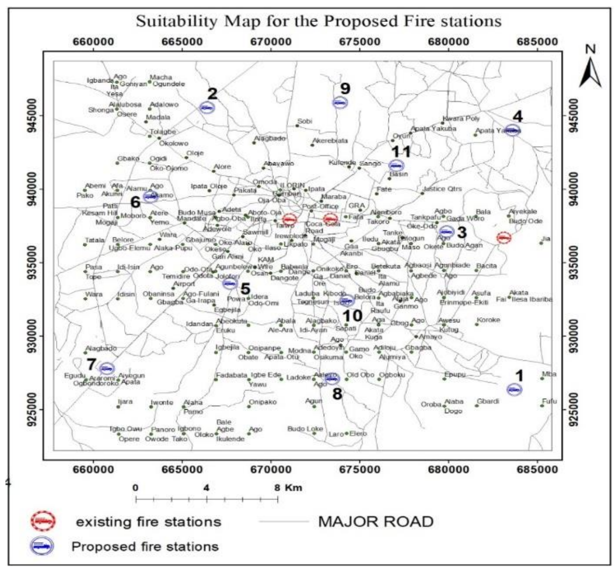

Figure 6. Proposed Fire station locations

The essential need for proposing new fire stations in the study area is as follows:

a) Fufu Area, Ilorin South Local Government (Station 1): A new fire station is proposed in this area due to its dense population and its surrounding areas such as Mba, Epupu, and Gbagba. Population density is the primary criterion for this suggestion.
b) Ilorin West Local Government (Station 2): An additional fire station is suggested in this area because there are parts of the study area that cannot be covered quickly in case of an outbreak. The proposed station would cover Mandala, Alalubosa, Goniyan, Okolowo, Macha, and its axis. The criteria considered for this suggestion are proximity to built-up areas and a water source (Sobi Dam).
c) Tanke Area, Ilorin South Local Government (Station 3): A new fire station is suggested in

this area, which covers Oke-Odo, Tipper garage, Pipeline road, Gaa-akanbi, and other surrounding areas. The area is highly populated and has hazardous material facilities. Criteria considered for this suggestion include population density, proximity to hazardous points, proximity to major roads, proximity to a water source, and proximity to built-up areas.

d) Apata Yakuba: A new fire station is proposed in this area due to its population, particularly because of the presence of Kwara State Polytechnic. This area is also outside the service area of existing fire stations.

e) Odo-Ota: A new fire station is proposed in this location to cover Geri Alimi, Airport, Ga-irapa, Odo-Omi, Gbagba, Egbejila, and surrounding districts. These districts have a high population and facilities with hazardous materials that require better fire protection.

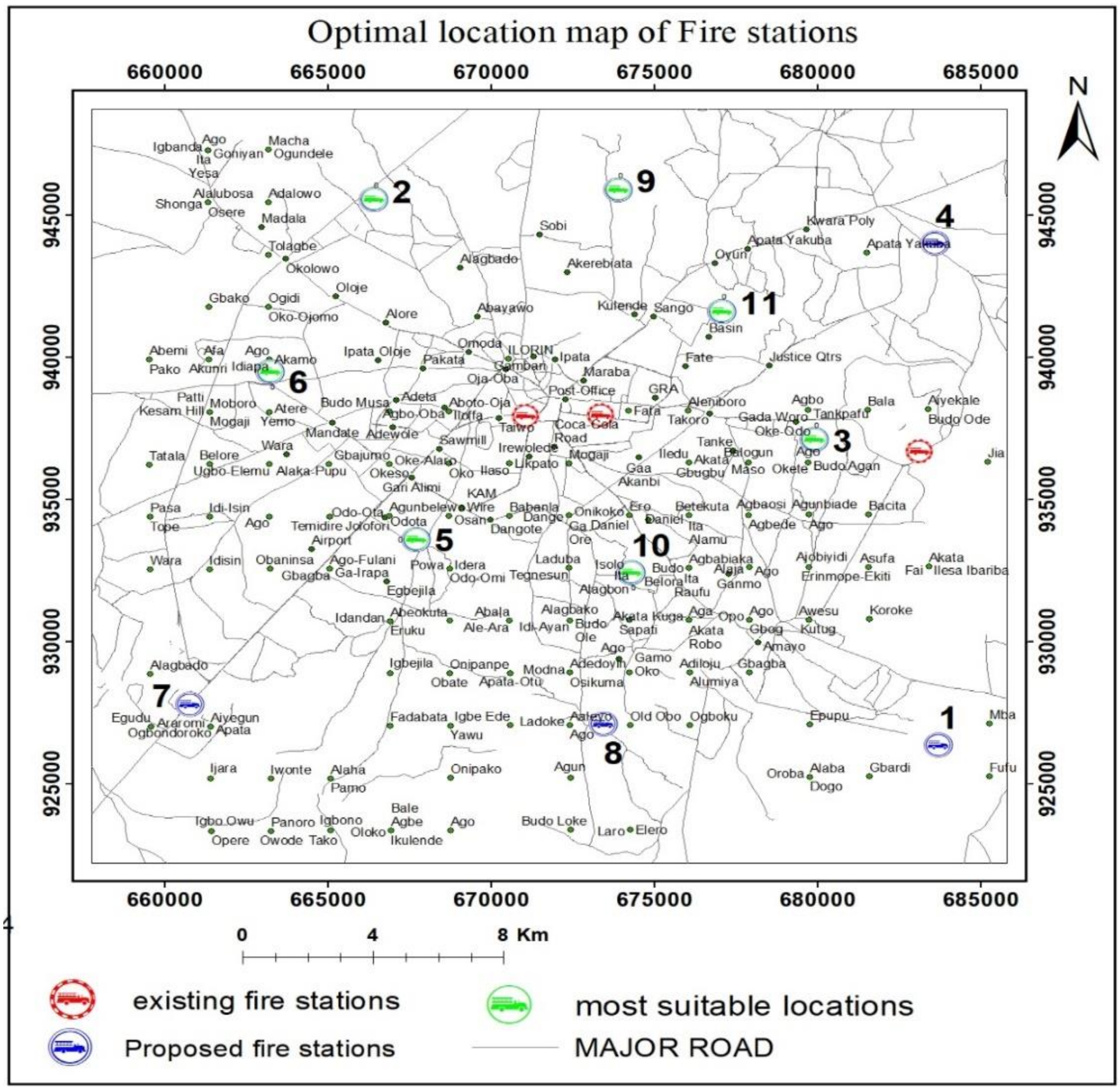

Figure 7: Map of optimal locations for site selection of Fire stations

f) Ago Akamo: This location is proposed for a new fire station due to its high population and being outside the coverage area of existing fire stations. It is located on the outskirts of the study area.
g) Araromi: Another location proposed for a fire station, it is highly populated and outside the coverage area of existing fire stations. It is also located on the outskirts of the study area.
h) Old-Obo: A fire station is suggested in this area, considering its proximity to Asa Dam. It is outside the service area of existing fire stations.
i) Sobi District: A fire station is proposed in Sobi District due to its proximity to Sobi Dam. It is also outside the service area of existing fire stations.
j) Agbabiaka District: This location requires a fire station to cover Ganmo, Amayo, Sapati, Laduba, and their surrounding areas. High population, proximity to hazardous points, water source, built-up areas, and existing fire stations are significant factors in this decision.
k) Basin District: A fire station is needed in this district to cover Fate, Oyun, Sango, Kulende, Justice quarters, and their surrounding areas. Similar criteria as mentioned above are considered for this suggestion.

These proposed locations are based on factors such as population density, proximity to hazardous points, proximity to a water source, proximity to built-up areas, and the coverage area of existing fire stations.

CONCLUSION

The integration of a technology designed to facilitate spatial decision-making into field emergency management has significant benefits in addressing various crucial geographical issues. GIS (Geographic Information System) plays a crucial role in emergency management, particularly in the placement planning of essential services like fire stations in metropolitan areas. To improve the site selection process, new and effective methodologies need to be applied.

In this study, the fusion of Analytic Hierarchy Process (AHP) with GIS provides decision-makers with a model for selecting the best locations for fire stations. The study discusses the functions of GIS and AHP in the selection of suitable locations, outlines the criteria for site selection, and presents case study findings for locating suitable fire station locations in the capital city of Ilorin, which is located in the Nigerian state of Kwara.

The rapid population growth and urbanization in Ilorin metropolis, as the administrative and economic center of Kwara state, necessitate the establishment of a highly effective and efficient fire emergency coverage service. The utilization of AHP in GIS combines decision support methodology with powerful visualization and analytical capabilities, significantly aiding in the identification of appropriate locations for fire services. This approach enhances decision-making in emergency management.

After conducting all the necessary analyses, the study proposes the establishment of 11 additional fire stations in addition to the existing two fire stations. These suggestions align with the standards outlined in Table 3, which guide the selection of suitable fire station locations.

References

1720:, N. F. (2010.). NFPA 1720: Standard for the organization and deployment of fire suppression operations,emergency medical operations and special operations to the public by volunteer fire departments.

Ahmadu et. al. (2021). Evaluation of Fire disaster Emergency Response Capacity uding Open-source Data and Response Time Analysis in Ilorin Metropolis. *Nigerian Journal of Environmental Science Technology*, 340-346.

Aziz, A. (2007). Fire Service Records Fires. *Daily Graphic online*, *Available from: http://www.graphic.com.gh. on 4/01/ 2014, page. 20.*, page 24.

Aen, I. Onden, T. Gokgoz, C. Sen. (2018). A GIS approach to fire station location selection. *Internation Information and Engineering Technology Association*.

Balamir, M. (1966). Fire Department Headquartes. *.MSc Thesis*, *Faculty of Architecture*.

Ball, M. and Lin, F. L. (2009). A reliability model applied to emergency service vehicle location. *Jounal of Operations Research,*, 41(1), 18-36.

Bing Han, M. H. (2021). Site Selection of Fire Stations in Large Cities Based on Actual Spatiotemporal Demands: Case Study of Nanjing City. *International journal of Geo-information*, 1-20.

Cheng, E. L. (2007). A GIS approach to shopping mall location selection. *Journal of Building and Environment*, 42, pp.884–892.

Chevalier, P. I. (2012). Locating Fire Stations: An Integrated Approach for Belgium,. *Socio-Economic Planning Sciences, Elsevier,* , vol 46(2), 173-182.

Chrissis, J. W. (1980). Locating Emerceny Service Facilities in a Developing Area. *Fire Technology*, *Department of Industriall Engineering and Operations Resarch*, *Virginia Polytechnic Istitute and State University*, Vol. 16, No.1, Virginia, pp.63-69.

Church, R. &. (2009). The maximal covering location problem. *Papers in Regional Science,*, 32(1), 101-118.

Dallas, N. (2009). *The report of the Nional Commision of Fire Prevention and Control.* Washington, D.C.: National Commission on Fire Prevention and Control, America Burning, .

EnviroIssues, E. J. (2008). *Fire Station 20 Siting Study Final Report.* Seattle, USA.: The Seattle Fire Department.

Erkut, E. F. (2001). *Improving the Emergncy Service Delivery in St. Albert.*

Erturgal I. and Karakasoglu N. (2008). Comparison of Fuzzy AHP and Fuzzy TOPSIS Methods for Facility Location Selection. *International Journal of Advance Manufacturing Technology.*, 783-795.

Galvao, R. & ReVelle, C. (2011). A Lagrange heuristic for the maximal covering location problem. *European Journal of Operational Research,*, 88(1), 114-123.

Habibi, K. L. (2008). Spatial Analysis of Urban Fire Station Locations by Integrating AHP Model and IQ Logic Using GIS, A Case Study of Zone 6 of Tehran. *Journal of Applied Sciences , University of Mazandaran, Iran.*, 3302-3315.

Hu, W. &. (2012). Urban road network accessibility evaluation method based on GIS spatial analysis techniques. *International Journal of Geographical Information* , 21(7), 757-776.

Ibrahim, R. B. (2014). Appraisal of urbanization trends in Ilorin, Nigeria. *Journal of sustainable development in africa*, 1-15.

Johnson, R. (2011). *Geographic Information Systems: A Powerful New Tool for Fire and EmergencyServices.* Retrieved 10 21, 2021, from ESRI LIBERARY: http://www.esri.com/liberary/whitepapers/pdfs /fire-ems.pdf

Liu, N. H. (2006). Optional siting of fire statios using GIS and ANT algothrim. *Journal of Computing in Civil Engineering*, 361-369.

Mardani, A. *et al*. (2015). Multiple criteria decision making techniques and their applications - a review of the literature 200 to 2014. *Economic Research-Ekonomska Isttrazivanj*, 516-571.

Marianov, V. & Serra, D. (2009). Location Problems in the Public Sector. *Journal of Geographical Systems*,, 22(2), 375-389.

Murray, A. and Tong, D. (2009). GIS and spatial analysis in the media. *Journal of Applied Geography*, 250-259.

Ohta, K. K. (2007). Analysis of the geographical accessibility of neurosurgical emergency hospitals in Sapporo city using GIS and AHP. . *International Journal of Geographical Information Science* , 22(5), 677–688.

Penjani, H.N. and Erden, T. (2020). A GIS-based fuzzy multi-criteria approach for optimal site selection of fire stations in Istanbul Turkey. *J. of Socio-Econ Planning Sciences*, 1-13.

Poerbo, I. H. (2001). Urban Design Guidelines As Design Control Instrument,with a case study of the Silver Triangle Superblock, Jakarta. *PhD Thesis, University of Kaiserslautern.*

Pondi, B. O. (2015). Application of GIS for Effective and Efficient Fire Disaster Emergency Response management(A case study : Mombosa County Fire Brigade in Mombaasa Island).

Prateille, D. &. (2010). Ambulance Management System using GIS . *MSc Thesis in Geoinformatics, Department of Computer and Information Science, Linköping University, Sweden*,, P. 78.

Saaty, T. (2013). The Analytic Network Process: Decision making with the analytic network process. *Journal of Mathematical Psychology*, 1-40.

Satty, T. (1980). Analytical Hierarchy Process: Planning, Priority Settings Resource Allocaton . *Journal of Mathematical Pshycology*, 231-281.

Şen, A. İ. (January 2015). A Gis approach to fire station location selection. *Gi4DM 2011 - GeoInformation for Disaster Management*, 1-7.

Toregas, C. S. (2009). The location of emergency service facilities. *Journal of Operations Research*, 19, 1363-1373.

Wang, W. (december 2019). Site Selection of Fire Stations in Cities Based on Geographic Information System and Fuzzy Analytic Hierarchy Process. *International Information and Engineering Technology*, 619-626.

Yang, J. Z. (2008). Accessibility: Concept, Measure And Application. *Geography and Territorial Research*, 15(2), 61-66.