Service area determination of fire stations in an urban setting through a GIS-based multi-criteria analysis: the case of Quezon City, Philippines

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Service area determination of fire stations in an urban setting through a GIS-based multi-criteria analysis: the case of Quezon City, Philippines

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Abstract: *The continuous rise of population and expansion in urban cities results in a higher demand for fire services making the determination of their service areas critical in emergency planning. This study aims to determine the service areas of the existing fire stations in Quezon City, Philippines through the use of a Multi-Criteria Decision-Making (MCDM) method of Analytical Hierarchy Process (AHP) integrated with Geographic Information Systems (GIS). The factors considered for the study are high population density (HPD), density of hazardous material facilities (DHM), distance to existing fire stations (DEF), and proximity to main roads (PMR) with associated AHP weights of 27.9%, 26.51%, 23.62% and 21.97% respectively based on the fire professionals involved in the emergency planning services. Results show that currently, 63.24% is covered by the existing fire stations. Based on the existing service areas and the gaps identified in the analysis, new stations were suggested to improve the coverage to 88.31%.*

Keywords: Service area, GIS, emergency planning services, AHP, MCDM

1. INTRODUCTION

Fire incidents constitute a major threat to life and property each year especially in the tropical regions [1,2]. With the alarming rate of global warming, fire cases throughout the years caused major casualties and irreversible damages within minutes of occurrence. The Philippines as a tropical country is not new to frequent fire incidents in both its rural and urban areas. In 2018, the Philippine Bureau of Fire Protection (BFP) recorded a total of 16,675 fire incidents in the country making the Philippines among the top 3 countries with the most fire cases in Asia as shown in Table 1 [3]. Velasco [4] noted that the numbers of fire and fire-related casualties stem from the fact that fire occurrences are relatively unstudied in the Philippines.

Table 1. Fire and Fire-related incidents in Asia, 2018

Country	Population (in million)	Incidents		
		Fires	Deaths	Injuries
India	1,359.0	1,600,000	12,747	-
Philippines	106.7	16,675	326	-
Rep. of Korea	51.6	42,338	369	2,225
Singapore	5.6	3,885	4	90
Vietnam	96.0	4,182	90	208

Source: World Fire Statistics, *https://www.ctif.org/*

Since the invention of fire engines in the early 1700s, fire stations have played an important role in the fire emergency response system in many cities [5,6,7]. In the Philippines, the Bureau of Fire Protection (BFP) is the primary agency responsible for fire prevention and fighting fire. As of December 31, 2017, there are only a total number of 145 fire stations in 81 provinces across the country, which is the minimum requirement under the Fire Code of the Philippines. However, not all the activated fire stations have their own fire truck and out of the 2,245 fire trucks nationwide, only 1,958, or 87 percent, are serviceable or in working condition [8].

Quezon City was selected as the focus of the study due to its high population density and its high number of recorded fire incidents in 2014-2018 [8]. It is part of the National Capital Region (NCR) and is located north-east of Manila, the capital of the Philippines. In terms of population and land area, it is the largest city in NCR with a population of 2.9 million according to the 2015 census and a land area of 161.1 sq. km. It is divided into six legislative districts with La mesa watershed covering the northern part of the city. Although there were 27 existing fire stations, Vallejo reported that the fire response time in the city is not within the ideal time because of factors like traffic congestion, obstruction of roads and narrow streets [8]. According to Erden and Coskun [10], a golden rule in fire emergency response is to set a 5 min constraint to ensure that the fire damage can be efficiently controlled by the fire fighters. Thus, the coverage area of each fire station should be limited so that all areas are reachable within 5 minutes. By identifying the service area of the different fire stations in Quezon City, critical areas can be identified, and additional fire stations can be proposed. This is to ensure an efficient fire response system to better handle the frequent fire incidents in Quezon City.

Fig. 1. Quezon City Map.

To ensure optimal fire response time, several studies [6,11,12,13] used the Geographic Information System (GIS) in determining the optimal locations and service area of fire stations. Service area mapping is a graphical representation of the analyzed data showing all accessible streets or road networks to assess the

accessibility of certain services. In the service area determination of fire stations, studies identified the following important criteria to be considered in the analysis: high population density (HPD), proximity to main roads (PMR), distance from existing fire stations (DEF), density of hazardous material facilities (DHM), wooden building density (WBD) and distance from the areas subjected to earthquake risk (DER) [10,12]. In most fire cases, the amount of land burnt were influenced by anthropogenic ignitions, fuel production, fuel fragmentation, and cultural behavior which are all linked to population density [13]. Moreover, in emergency services, access and service coverage reflect the dominant concern of response time in fire rescue and emergency medical services [14]. This includes road accessibility [15], proximity to the road, existence of commercial centers and the existence of worn-out structures [16]. According to Edelstein [17], with the presence of hazardous facilities, the perception of risk of the locals within the vicinity is higher than that of a normal neighborhood. Thus, establishments that deal with fire hazards like LPG, paper and textiles, explosives, harmful chemicals, wood and electrical are most prone to fire incidents if not provided with safety precautions.

In this study, since Quezon City is highly urbanized, HPD, PMR, DEF, and DHM criteria were considered. Although the effects of WBD and DER are also relevant, data on these criteria are harder to acquire given the constraints of the pandemic. The criterion with the greatest impact in determining the service areas was also identified using Analytic Hierarchy process (AHP). GIS tools were then used in generating service area maps of the existing fire stations in Quezon City to identify critical areas or areas that are still not serviceable by any station. This study aims to map and assess the fire stations in Quezon City considering that fire station service area studies in the Philippines are scarce, especially in urban settings.

2. METHODOLOGY

2.1. Data collection

Primary data collection was not done due to the restrictions of the COVD-19 pandemic. All necessary secondary data (barangay shapefile, fire station locations, road network shapefile, population density, treatment, storage, and disposal (TSD) facilities) were gathered from different sources online through official requests to the official government websites.

Liu et al. [19] used the Global Positioning System equipment terminal of online maps such as Google Maps in obtaining real time data of speeds and travel time. In this study, travel time and vehicle speeds were gathered during A.M. peak hours (7:00 - 9:00 A.M.), noon peak hours (11:00 A.M. - 1:00 P.M.) and afternoon peak hours (4:00 - 6:00 P.M.). For three weeks from October 21, 2021 to November 11, 2021, one recording of travel data was done per hour of each period every day.

2.2. Raster data set creation

For the DEF criterion, the speeds of the Quezon City road network were used in ArcGIS to perform service area analysis based on travel time impedance alone. Using the network analyst tool, a time impedance of 1, 2, 3, 4 and a maximum of 5 minutes was used to limit the fire response to 5 minutes or less. For the HPD criteria, the 2020 Census of Population obtained online from the Philippine Statistics Authority (PSA) was used to develop a population density map. The population density (capita/hectare) of each barangay in Quezon City was calculated using the Geometry Calculator in ArcGIS to come up with the area polygons of each barangay. For the DHM criteria, the density of hazardous material facilities shapefile was developed by adding the total number of TSD facilities in each barangay. Lastly, the PMR criterion map was created from the road network map developed in 3.1. From the road network layer, a multiple ring buffer analysis was done with an incremental distance of 60 m, 120m, 180m, 240m and 300 m [20].

2.3. Raster data set reclassification

From the criteria shapefiles of DEF, HPD, DHM, and PMR, 5 classes of representation were made for the reclassification of the raster maps with 5 being the highest priority and 1 being the lowest priority in service area determination of fire stations. According to Erden and Coskun [10], the tone scale for class representation should not exceed seven tone values, therefore, the criteria value ranges were divided to equal interval breaks from 1 to 5. For the DEF criterion, the higher time travel in area coverage has the highest priority as these areas are the farthest from the existing fire stations. Barangays with higher population density have higher criteria values as it is more likely that a fire incident can occur in a populous area. Closer areas to the primary roads are preferred for new fire station locations as the fire vehicles can easily access these roads in proximity. Lastly, fire incidents are more likely to occur in areas with numerous hazardous material facilities which are the highest priority in the criteria values. All criteria shapefiles were then divided into 5 equal breaks. Table 2 shows the criteria value ranges and their respective reclassified class values for the raster data set.

Table 2. Criteria value ranges

	Reclassified class values				
Criteria	1	2	3	4	5
DEF (minutes)	1	2	3	4	5
HPD (people per hectare)	16-335	336-655	656-974	975-1294	1295-1613
DHM (facilities per barangay)	0	1	2	2-3	3
PMR (meter)	300-240	240-180	180-120	120-60	60-0

2.4. Analytic Hierarchy Process

AHP analysis was utilized as a primary method in the multi-criteria decision-making process. In finalizing the criteria weights of DEF, HPD, DHM, and PMR in the service area analysis, 13 professional experts in the fire emergency response and fire service personnel that are part of the planning services of the BFP were surveyed using Google Forms. In this survey, the profiles of the experts who responded were fire service department personnel, fire inspectors, and emergency management

professionals. The respondents were asked to rank the 4 criteria from 1-4 according to their level of priority in determining the service area of the fire stations with 1 being the highest priority and 4 being the lowest priority. The importance of each factor was also scored from 1-5 with 1 being poorly important and 5 being highly important to check the level of difference between factors. Analysis was done through pairwise comparison of criteria, estimation of relative weights, calculation of consistency ratio to indicate acceptable level of consistency, and the aggregation of all the relative weights of the decision criteria. From the score gathered in the survey of professionals, pairwise comparison was scored according to Saaty [21] where: equal importance = 1, moderate importance =3, strong importance = 5, very strong importance = 7, and extreme importance = 9.

2.5. Weighted overlay analysis

The scores given by the professionals were converted and the following consistency ratios were checked to see if these values were acceptable. The weight vectors for each of the four criteria were then calculated. The final weights of the criteria maps were obtained by calculating the statistical mean of the weights of the criteria.

The values were reclassified from the shapefiles to each criterion map layer from values of 1 to 5, the resulting raster maps were then overlaid by the resulting criteria weight from the AHP procedure. A multi-criteria analysis was done with the 4 criteria PMR, HPD, DEF, and DHM by using the Spatial Analyst extension of the ArcGIS program. In this analysis, all the 4 criteria were simultaneously analyzed based on the respective weights of each criterion that produced the service area map of the fire stations.

2.6. Fire station site selection

From the service area map of the fire stations determined through ArcGIS, critical areas were defined as areas that are not serviceable by any of the fire stations located in Quezon City. Nyimbili and Erden [12] suggested that a raster suitability map should be produced from ArcGIS to objectively show the most feasible locations for new fire stations considering the criteria set in the weighted overlay maps. The areas in the existing fire station service area map with a reclassified value of 4 or 5 were chosen for the proposed location of fire stations as these areas are of high priority based on the multi criteria analysis. The road accessibility was also considered in choosing for the location of additional fire stations. The same final criteria weights developed from the AHP procedure were used in the final analysis of suggested locations for constructing fire stations that can provide service to the identified critical areas in Quezon City and the percent coverage of these areas were compared. Aside from the areas with priority levels of 4 and 5, some areas that are not within the service areas of the fire stations were considered in choosing for a fire station location. With the new fire stations included, the same weighted overlay analysis was done that produced a new service area map and the new percentage served by the fire stations was quantified.

3. RESULTS AND DISCUSSION

3.1. Criteria shapefiles

The figures below show the produced DEF, HPD, DHM and PMR criterion maps. The maps show the reclassified values of each criterion from 1 to 5 with 5 as the highest priority in fire station selection based on the specific criterion.

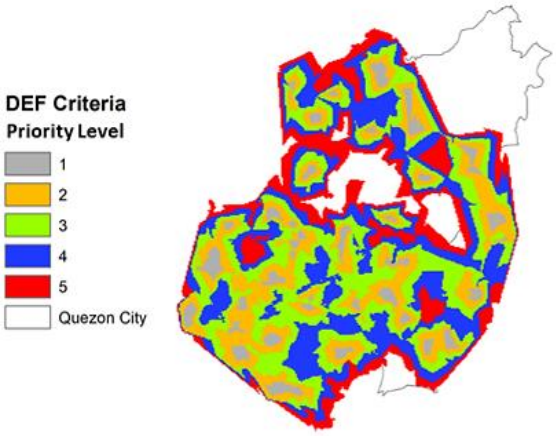

Fig. 2. DEF criterion map.

The figure above shows the DEF criterion map produced using service area analysis based on travel time impedance alone from 1 to 5 minutes. The areas in the northern regions specifically at Lamesa watershed are not covered as there are no existing fire stations in these areas. Even though there are road segments in these areas in the northern regions, these areas are not covered within 5 minutes of travel time as the existing fire stations are distant from this region. On the other hand, areas in the central region of the city are not also covered in the 5-minute travel time as there are no road segments present in this region. With this, fire vehicles stationed in nearby fire stations cannot access these areas and therefore are not covered in a 5-minute travel time. Areas with criteria value of 5 shows that these areas are of utmost priority during a fire emergency as it takes 5 minutes of response time before the fire vehicles reach these areas.

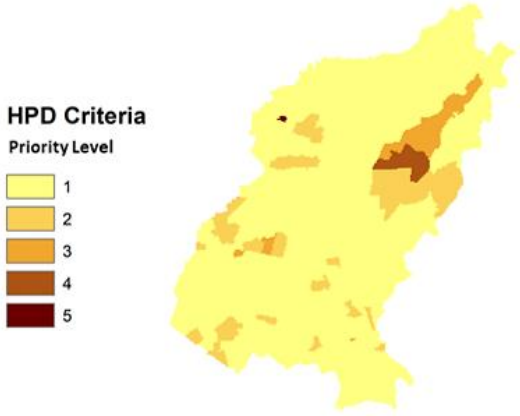

Fig. 3. HPD criterion map.

In this criterion, barangays with high population density are of the utmost priority during a fire emergency [12]. Only one barangay in the city was identified with the highest population density. This means that this barangay is at the top priority if a fire emergency occurs when the

only criterion considered in the emergency response is the population density.

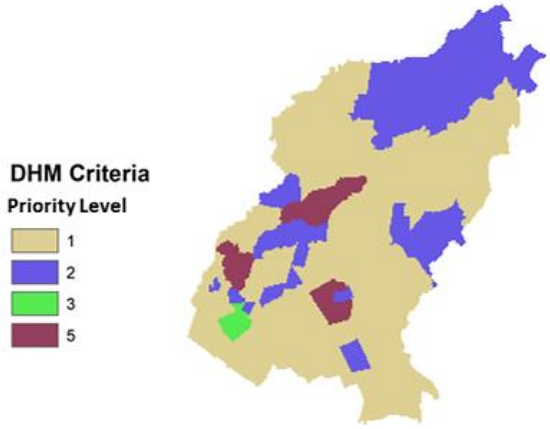

Fig. 4. DHM criterion map.

Fig. 4 shows the DHM shapefile produced by adding the total number of TSD facilities in each barangay. Since the maximum number of TSD facilities in a barangay is only at 3, the reclassified value for the DHM was set such that the maximum number of TSD facilities in a barangay would have a value of 5, and the remaining values below were proportioned to this value. A higher priority level was assigned to the barangays with a larger density of hazardous material facilities [10] which means that the barangays with the highest number of TSD facilities are at the utmost priority if a fire emergency occurs when the only criterion considered in a fire emergency response is DHM.

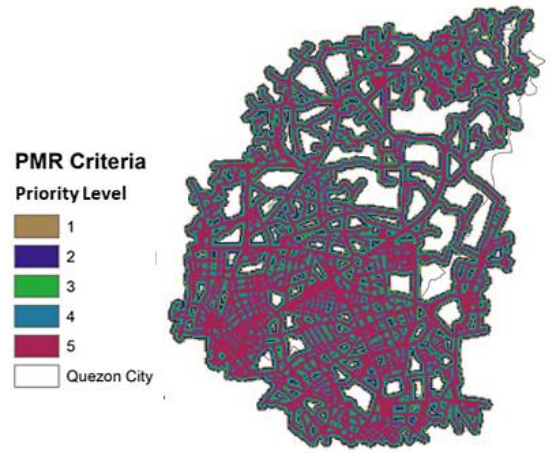

Fig. 5. PMR criterion map.

Fig. 5 shows the resulting PMR criteria map produced from the buffer analysis done through ArcGIS. This criteria map was divided into 5 equal increments of 60 meters each from 0 to 300 which was reclassified to values from 1 to 5. The highest priority level in this criterion are the areas that are closest to the road segments present in the city as these areas are highly preferred for new fire station locations to provide easy access for the fire vehicles to respond during a fire emergency. Some areas are not covered in this criteria map as there are no road segments present in these barangays for the emergency response team to reach these areas. In considering only the PMR criterion in fire station selection, the areas that are distant from the road segments are not prioritized.

3.2. AHP criteria weights

Table 3. Final criteria weights

Criteria	Priorities/Weights
HPD	0.2790 (27.90%)
DHM	0.2651 (26.51%)
DEF	0.2362 (23.62%)
PMR	0.2197 (21.97%)
SUM	1 (100%)

Table 3 shows the normalized weights for all the four criteria chosen in the multi-criteria decision-making procedure with a mean consistency ratio of 0.006. The AHP shows that the high population density criterion has the highest priority/weight among all four criteria in determining a service area of a fire station according to the surveyed fire professionals. This indicates that the 13 academic professionals and fire emergency response personnel viewed HPD as having the greatest influence in considering a service area of a fire station. According to the 2020 census data of Quezon City, the city has a population of about 2,960,048. With a total area of approximately 161 square kilometers, the city is the most urbanized and most populous city in the National Capital Region [22]. Over the last decade, Quezon City's population has increased by 7.18% which also resulted in an increase in infrastructure construction projects as part of the expansion of the city; in these years, there has also been a continuous rise in fire emergencies and occurrences [23,24]. The DHM criterion on the other hand indicated a lower priority at 26.51% compared to a previous study for optimal site selection of fire stations done in Istanbul, Turkey with a weight of 40.0%. Unlike Quezon City, Istanbul is heavily consisted of hazardous material facilities and numerous fire incidents caused by heavy industrial activities [10]. The city of Istanbul has a district with a maximum total of 19 hazardous material facilities while Quezon City only has a maximum of 3 hazardous material facilities in a barangay which resulted in a lower priority in this study. The DEF and PMR criterion on the other hand have lower priority levels same with the study of Erden and Coskun 2010. This is because multiple fire stations are more desirable in responding to higher risk levels of fire incidents [10]. In the study of Erden and Coskun [10], the difference between the highest and the lowest criteria weight is at 30% while in this study, the highest criteria weight (HPD) was only 5.93% higher than the lowest criteria weight (PMR). This shows that there is no criterion among the 4 chosen in this study that has extreme high values that could significantly change the final decision result unlike in the studies in the Istanbul wherein the HPD and the DHM criteria are significantly higher due to a large

annual population growth rate and high number of industrial activities respectively.

3.3. Final service area

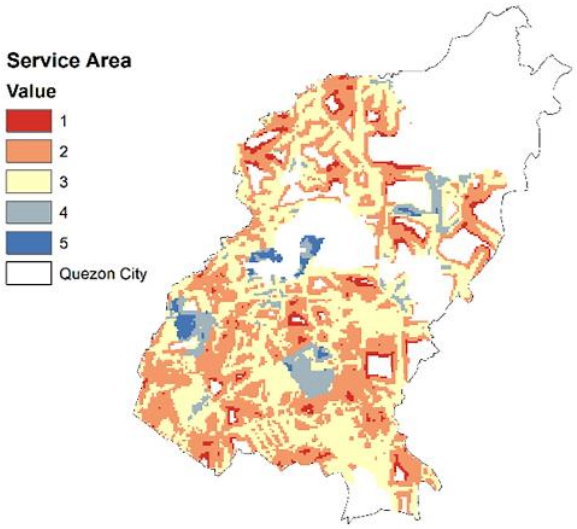

Fig. 6. Current service area of existing fire stations.

Fig. 6 shows the service area of the existing fire stations in Quezon City. The service area map was analyzed through ArcGIS to determine the percentage area coverage of the whole service area map as well as the distribution of the priority levels of the map. Note that these priority value levels were reclassified to simply show the different priority levels of the service area map. The highest priority to be responded during a fire emergency of the initial service area map is at 3.53 to 4.16 which means that no area in the city reached the highest or peak priority level from the multi-criteria analysis. The service area map in Fig. 6 showed that the existing fire stations can cover a total of 63.24% of the total area of Quezon City.

Fig. 7 shows the service area map of the existing fire stations and the different barangays that are not serviceable in the city. The Lamesa dam area at the northern region of the city is not within the service area map due to the lack of the fire stations in that region. No fire vehicles are situated in that region that can respond to the area within the 5-minute response time. In the middle region of the city, most of the areas in the barangays Pasong Tamo and Tandang Sora are also not serviceable due to the absence of the road segments. This situation can also be seen in the areas of barangays Loyola Height and Pansol at the eastern region of the city. Even though there are nearby fire stations in the city as well as close areas that are within priority levels of 1 and 2, these barangays are not serviceable because the fire vehicles cannot travel to these areas without the connecting road segments. The Barangay Ugong Norte at the southern region, on the other hand shows that most of its area are not serviceable due to the lack of fire stations in that area, same with the barangay Matandang Balara in the eastern region and Payatas and Commonwealth at the northern region. However, there is no main reason or indicator that a sole criterion affects the serviceability of a critical area as in this analysis, all criteria were taken into consideration and the final service area map shows the overall analysis done through the program using all the criteria chosen for the study. It completely indicates on the other hand that these critical areas are not within the 5-minute response time of the existing fire stations considering all the criteria chosen for the study.

3.4. Critical area

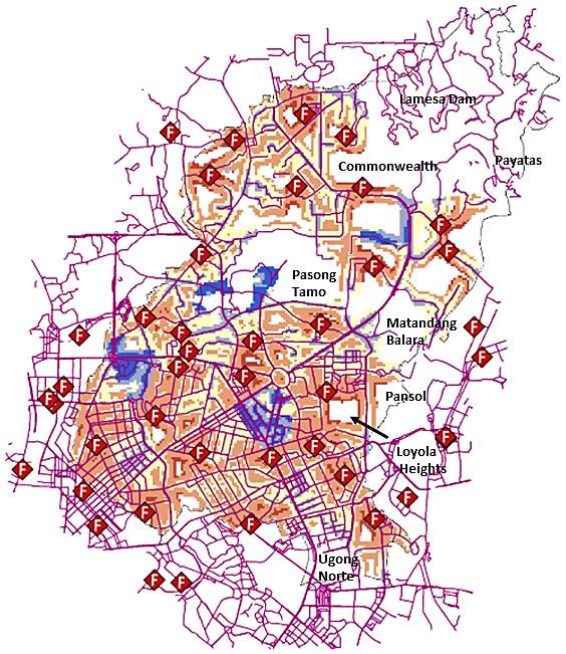

Fig. 7. Service area map overlaid with road network shapefile.

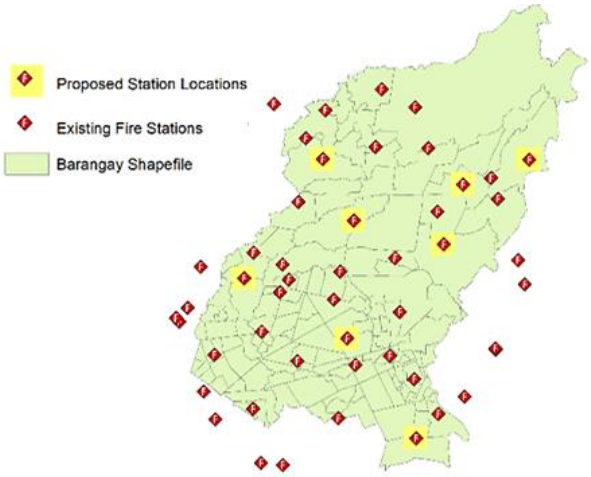

Fig. 8. Existing and proposed fire stations shapefile.

From the existing service area map, 8 fire station locations were identified. Looking at the service area of the existing fire stations in Fig. 6, the new fire station locations were optimally located at the priority levels of 4 and 5 as these levels are close to the critical areas in the study area. Other proposed fire stations were located at the critical areas that are not within the service area of the existing fire stations such as the areas in Loyola Heights, Matandang Balara and the Payatas region. Both these critical areas and high priority levels were considered as these are the optimal locations for the new fire stations to cover more unserviceable areas in the city. Proposing fire station locations in lower priority levels will result in

overlapping service areas with the existing fire stations thus lessening the increase in the total coverage area of the city. The road accessibility was considered in choosing for an optimal location of the additional fire stations as ArcGIS would encounter an error in the Road Network Analyst if a proposed fire station location is not near a road segment in which the fire vehicle would travel.

3.5. New service area with proposed fire stations

Including the new proposed fire stations, a new service area map was developed using the same multi-criteria analysis done for the existing fire stations.

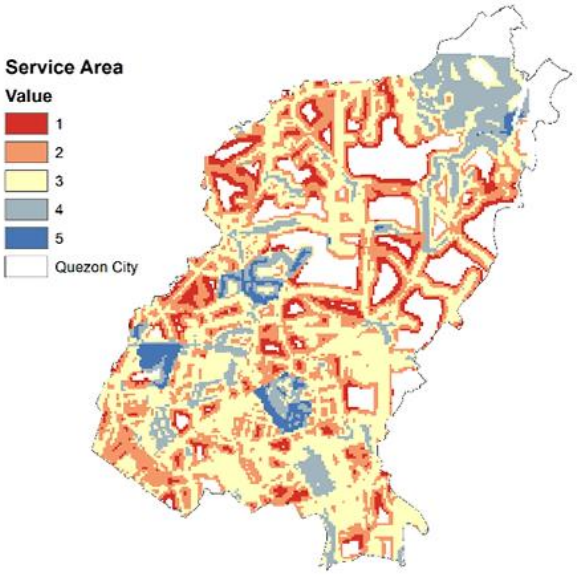

Fig. 9. Service area of existing and proposed fire stations.

As seen in Fig. 9, the new service area map with the 8 proposed fire stations showed a larger area coverage of the city with an 88.31% service area coverage compared to the previous 63.24% coverage rate. With the new proposed fire stations, areas at the Payatas and Commonwealth of northern region that are now serviceable. Priority levels in this region are still at a high level with values of 4 and 5 which means that more fire stations in these areas could still be added. The Lamesa dam area as well are now covered within the 5-minute emergency response with priority level of 4 as seen in the figure above. Note that these areas are close to the dam itself which is why no more fire stations were proposed and that they are already reachable by the new fire stations proposed. However, areas at the Pasong Tamo and Tandang Sora are still not serviceable due to the inaccessibility of the roads. No more fire stations can be added as this is directly limited by the road accessibility and would result in error in analysis as the proximity of the main roads are too far. Most of the areas in the Ugong Norte at the southern region of the city are now serviceable. There are still some areas in these regions that are not serviceable due to the road inaccessibility as well. Overall, the additional 8 fire stations increased the total coverage area of the fire stations in the city by an additional 25.07%.

4. CONCLUSION

This study showed how AHP, and GIS can be used in a multi-criteria analysis, especially in determining the current service area of a facility and a possible model for optimal suitable locations. The combination of the analytical process of AHP and the spatial data analysis of GIS have optimally located new suitable locations for the fire stations in the study area. This process can be used in enhancing the quality of different decision-making processes for site selection in emergency planning services.

In this study, four criteria were identified in affecting the service area of a fire station namely: high population density (HPD), density of hazardous material facilities (DHM), distance to existing fire stations (DEF) and proximity to main roads (PMR) with priority weights calculated through AHP at 27.9%, 26.51%, 23.62% and 21.97% respectively. Using these criteria weights, multi-criteria analysis was done in ArcGIS to produce a service area of the fire stations in Quezon City which showed that only 63.24% of the total land area of the city is serviceable. The service area of the fire stations during weekends has a larger coverage rate of 71.26% compared to the service area during weekdays with a coverage rate of 62.77%. Most of the areas that are not serviceable by the existing fire stations are due to the road inaccessibility such as barangays Pasong Tamo and Tandang Sora in the middle region as well as the barangays of Loyola Heights and Pansol in the eastern region of the city. Another factor is the absence of nearby fire stations which limited the emergency response in the southern region of the city at barangay Ugong Norte as well as the barangay Matandang Balara in the eastern region and Payatas and Commonwealth in the northern region.

Based on the analysis, higher priority levels of 4 and 5 from the service area of the existing fire station indicate that these areas are the most suitable location for the new fire stations. In this study, the researchers proposed 8 new urban fire station facilities in both the high priority levels of the city as well as in areas that are not within the service area of the existing fire stations. These additional fire stations increased the total service area of the existing fire stations by 25.07% providing service to critical areas as well such as the Lamesa dam in the northern region, barangay Ugong Norte in the southern region and decreased the critical areas in the barangays Matandang Balara, Loyola Heights, and Pansol in the eastern region of the city.

5. RECOMMENDATIONS

Improved modification of AHP named fuzzy AHP can be used in future research in which the uncertainty of the professionals interviewed for the priority weight calculation is considered. With this, a proper weight assignment would be used in the multi-criteria analysis providing more accurate service area maps.

For future studies, it is also recommended to study the economic feasibility of the proposed fire station locations and take different factors in determining these locations such as: continued infrastructure and settlement expansions, tourist hotspots, trading hotspots, and varying increase in population especially in industrial and commercial areas. Collaborate with the authorities in consulting about the financial requirements and the allowable budget in constructing new fire station

facilities. Aside from this, also consider the fire station capacities as well as the availability of fire trucks in responding to a fire emergency. The fire intensity could also be checked as the probability of needing more than one station in responding to a fire incident can be taken into account in considering the service area of the fire stations in the city.

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