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Landfill Site Suitability Mapping Using Fuzzy Multi-Criteria Decision Analysis and GIS: Case of Quezon City, Philippines

Noriza T. Sadie[1*], Maria Antonia N. Tanchuling[1], Ariel C. Blanco[2]
[1]*Institute of Civil Engineering, University of the Philippines Diliman, Quezon City, Philippines,*
[2]*Department of Geodetic Engineering, University of the Philippines Diliman, Quezon City, Philippines*

Abstract — *Most of the municipal solid waste generated in the Philippines is disposed in dumpsites and landfills. However, many of these disposal facilities have already reached their maximum capacity, and thus new locations must be sited. The Philippines' Republic Act 9003 mentions criteria for the landfill site selection but some of these parameters have no quantitative value. The lack of appropriate and intensive methodology in the country also makes it difficult for the local government units to identify areas within their scope. This study aims to present a methodological framework for identifying municipal landfill sites in the provinces of Bulacan and Rizal for Quezon City's waste. The framework involves Fuzzy Multi-Criteria Decision Analysis (FMCDA) combined with the use of GIS to aid in the site selection. Since siting a sanitary landfill requires extensive evaluation procedures to identify the best available landfill site, the procedure in this study employs every critical requirement such as government regulations and minimum impact in the environmental, social, and economic aspects. A final list of 14 factors and constraints, along with their corresponding weights and attributes as obtained from the legislature, literature, and experts' opinion, was considered. Using magnitude method for defuzzification and weighted linear combination for aggregation, a final suitability map was presented. Further, 26 areas were identified as highly suitable sites, 3 of which can be considered as potential candidate sites in accordance with economic viability as imposed by the government of Quezon City.*

Keywords — FMCDA, GIS, magnitude method, municipal solid waste, site selection, suitability map

I. INTRODUCTION

1.1 Background

One of the inevitable products of human civilization is municipal solid waste (MSW). The management of MSW consists of waste minimization, collection, processing, recovery, re-using, recycling, and disposal. Even if a combination of these management techniques is utilized and the strict implementation of waste reduction and recycling is applied, sanitary landfills are still necessary in an MSW management system. It still remains as the final destination of waste irrespective of the technology used [1, 2]. However, less attention has been paid to use engineering knowledge to locate the most suitable location for these disposal sites. Since landfill selection is a critical issue in urban planning processes, the need for engineering knowledge and application is essential.

Due to the lack of technical expertise and financial constraints, numerous local government units in the Philippines are still operating illegal disposal facilities [3]. Open dumpsites and controlled disposal facilities are still operational in spite of the Philippines' Republic Act 9003:

Ecological Solid Waste Management Act of 2000 (RA 9003) which mandates all the local government units to close these illegal disposal facilities [3, 4]. Also, with the growth of urbanization and population in the Philippines, larger amount of waste are produced every year. Because of this, some of the disposal facilities in the country, including the Payatas Controlled Disposal Facility in Quezon City have already exceeded their maximum capacity. Therefore, in order to meet the country's landfilling needs, new locations must be sited.

Landfill site selection is generally composed of two major steps namely, the identification of potential sites through initial screening and the ranking and evaluation of the suitability of these potential sites, which makes it a difficult, complex, tedious and protracted process [5]. Currently, the landfill siting and screening methodology of the government is composed of data acquisition, manual plotting of excluded areas on an appropriate map, identification of candidate sites from the map for field surveys, evaluation, and selection of the preferred site [6]. Manual overlays can be used with a high degree of success [7], however this methodology is very time-consuming and tedious.

The Implementing Rules and Regulations (IRR) of RA 9003 [8] mentions absolute and conditional criteria for the landfill site selection. However, these criteria have equal weights (i.e., priority is not given to the more important factors) and some of the parameters mentioned have no quantitative value. The lack of proper and intensive methodology for landfill site selection also makes it difficult for the local government units (LGUs) to identify areas within their scope. Therefore, there is the need to adopt methods that will incorporate all these concerns during the selection.

1.2 Geographical Information System

The Geographical Information System (GIS) is "a digital database management system designed to manage large volumes of spatially distributed data from a variety of sources" [9]. For the site selection in GIS systems, the factors, criteria, and the constraints availed as map layers are processed and analyzed [10]. With the development of GIS, the difficulties encountered in the landfill siting process can be lessened. For instance, one of the advantages of making use of the GIS-based approach in landfill siting is that it greatly reduces the time and cost of selection and provides a digital data bank for the long term monitoring of the site [11].

1.3 Fuzzy Logic

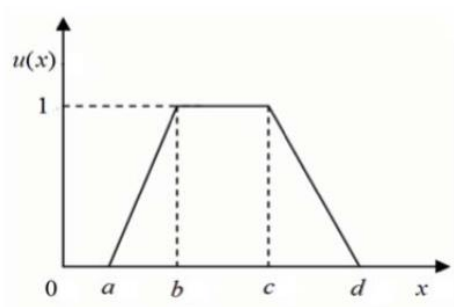
Conceptually and algorithmically, fuzzy sets [12] constitute one of the most fundamental and significant notions in science and engineering [13]. The application of fuzzy sets to preference modeling and analysis of decision-making problems delivers a flexible environment, which allows dealing with the inherent uncertainties of perception [13].

While the process of dichotomization imposes a binary, all-or-none classification decision, fuzzy sets loosen this requirement by acknowledging intermediate values of membership. Values between 0 and 1 can be applied to quantify human perception on how compatible these values are with the class: 0 being incompatible and 1 being fully compatible. Allowing for gradual, hence less strict, membership degrees is the bottom line of fuzzy sets [12,13].

Zadeh (1965) proposed a series of fuzzy membership functions that could be classified into two groups: the linear fuzzy membership functions and the non-linear fuzzy membership functions. In conducting the inference, linear membership functions are commonly used to describe the vagueness and ambiguity in the real-world system [14]. For the purpose of this study, we employ the use of linear membership functions.

1.3.1 Fuzzy Set Preliminaries

A trapezoidal fuzzy number A=(a,b,c,d), is a piecewise linear function characterized by four parameters, “a”, “b”, “c”, and “d”, each of which defines one of the four linear parts of the membership function. It assumes the following form:



$$u_A(x) = \begin{cases} 0 & if\ x < a \\ \dfrac{x-a}{b-a} & if\ x \in [a,b] \\ 1 & if\ x \in [b,c] \\ \dfrac{d-x}{d-c} & if\ x \in [c,d] \\ 0 & if\ x > d \end{cases} \qquad (1)$$

Figure 1. Trapezoidal Fuzzy number A=(a,b,c,d)

When b=c, the trapezoidal fuzzy number becomes a triangular fuzzy number A=(a,b,d).

A trapezoidal fuzzy number in parametric form u is a pair ($\underline{u}$, $\overline{u}$) of functions $\underline{u}$ (r), $\overline{u}$ (r),0≤r≤1, which satisfy the following requirements [15]:

i. $\underline{u}$ (r) is a bounded monotonic increasing left continuous function,
ii. $\overline{u}$ (r) is a bounded monotonic decreasing left continuous function,
iii. $\underline{u}$ (r)≤ $\overline{u}$ (r),0≤r≤1.

The trapezoidal fuzzy number u(x_0,y_0,σ,β), with two defuzzifier x_0,y_0, and left fuzziness σ>0 and right fuzziness β>0 is a fuzzy set where the membership function is as

$$u(x) = \begin{cases} \dfrac{1}{\sigma}(x - x_0 + \sigma), & x_o - \sigma \le x \le x_0 \\ 1, & x \in [x_0, y_0], \\ \dfrac{1}{\beta}(y_0 - x + \beta), & y_o \le x \le y_0 + \beta, \\ 0, & otherwise \end{cases} \qquad (2)$$

And its parametric form is

$$\underline{u}(r) = x_0 - \sigma + \sigma r, \qquad \overline{u}(r) = y_0 + \beta - \beta r.$$

Provided that x_0=y_0 then u is a triangular fuzzy number, we write u=(x_0,σ,β).

For this study, the trapezoidal and triangular fuzzy numbers will follow the general form: a=(a,b,c,d) and a=(a,b,d). The parametric form, on the other hand, will be used for computation purposes only.

1.4 GIS and FMCDA in landfill site selection

Regarding the problems related to decision-making on the siting of MSW landfill, it can be said that making decisions is not that simple and the speed and precision are reduced due to the lack of standards [11]. With this, the multi-criteria decision analysis (MCDA) was designed. Some studies on landfill siting have integrated GIS and MCDA in various ways. For instance, Akbari et al. [16] presented a paper that uses an integrated approach to construct a spatial decision support system (SDSS) via two-stage analysis combining GIS and fuzzy MCDA in the landfill site selection in Bandar Abbas, Iran. GIS was used to eliminate areas deemed unacceptable as landfill sites while the FMCDA was applied to rank the probable sites and summarize the final selection. In the first stage, internal and external weightings are applied to the remaining areas. In the second stage analysis, the pros and cons of the different candidate sites are evaluated with respect to different predetermined criteria. The criteria that were selected for evaluations are: 1) protection from strong winds, 2) transportation issues, 3) altitude, 4) size and shape of landfill, and 5) public health, safety nuisance.

Moeinaddini et al. [11] evaluated the suitability of Karaj, Iran to optimally site a landfill for the region using analytic hierarchy process (AHP) and weighted linear combination (WLC) in a GIS environment. A primary screening was not performed and the whole region was evaluated for the siting of the landfill. IDRISI software was used to combine GIS functions and MCDA approaches. The evaluation criteria used in the study were classified into four main categories, namely, the physical characteristics of the land, buffer and distances, the visibility, the sensitivity of the ecosystem and the land use and land cover. This is further classified into sub-criteria. The maps are standardized by fuzzy functions after digitizing or importing and converting to a raster format of 30m pixel size. WLC was used to find suitable alternatives for landfilling along with the pair-wise comparison matrix (PCM) to determine the weights. As discussed by Robins [17], the decision-making group in the PCM should be a minimum of five to a maximum of about fifty.

On the other hand, De Feo et al. [18] developed a procedure that minimizes the wasting space for the siting of hazardous waste landfills given the shortage of land for waste disposal in urban regions and provided a more reliable and convincing hierarchy of suitable sites. The study also used MCDA approach using the “priority scale” along with the AHP and compared it to the Paired Comparison Technique in combination with the Simple Additive Weighting method. The three phases of the siting process were also discussed. The first phase is aimed at selecting non-suitable areas as well as potentially suitable areas on the basis of an excluding criteria defined by the legislation. The second phase, which is the spatial multi-criteria analysis, is aimed at identifying list of sites with the use of “preferential and penalizing criteria”. The third phase is the final selection of the most suitable site among the potentially suitable.

Majority of the methods in landfill site selection are generally composed of the identification of potential sites through initial screening by GIS and the ranking and evaluation of the suitability of these potential sites by MCDA. The other methods, on the other hand, involve advanced mathematical procedures that are scarcely suitable for decision makers or users if they are to use fuzzy set theory for the first time [19]. Thus, this study proposes combining GIS and FMCDA in one integrated method. To achieve this, fuzzy estimates from experts' opinion and weighted linear combination (WLC) in GIS environment are employed in this study. This integrated method will provide a landfill suitability map that can readily determine the ranking of suitable sites based on their factors' scores.

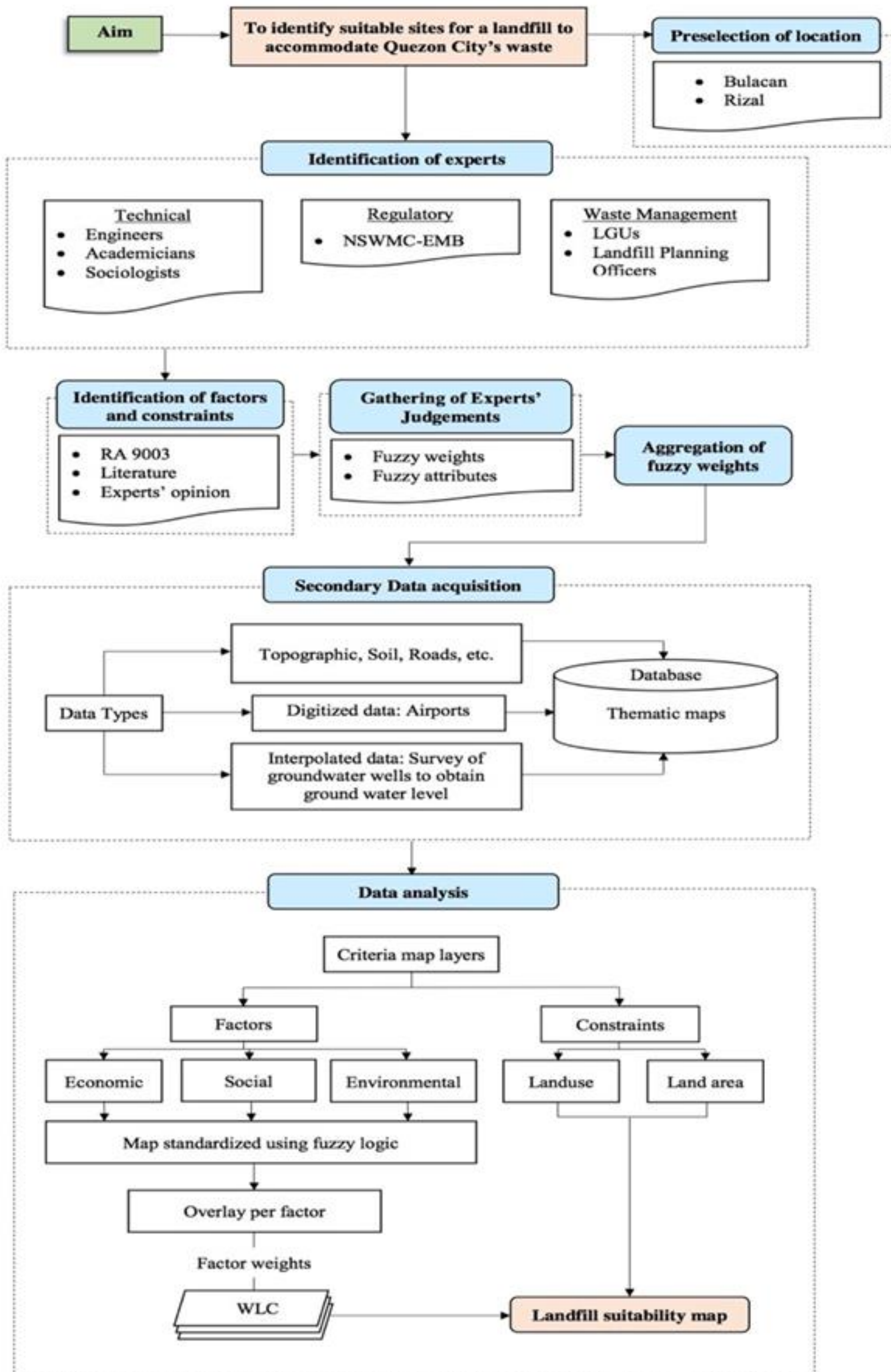
1.5 Objectives

This study aims to present a methodological framework for identifying municipal landfill sites specifically in the provinces of Bulacan and Rizal for Quezon City's solid waste. This framework involves fuzzy multiple criteria decision analysis (FMCDA) combined with the use of GIS to aid in the site selection.

The output of this study is a final list of criteria to be considered in landfill siting along with their corresponding weights and attributes to eliminate the subjectivity associated in choosing landfill sites on a local level. Furthermore, a final suitability map of MSW landfills incorporating the factors identified by the legislation, literature and experts' opinion shall be presented. Finally, from the resulting suitability map, highly suitable areas shall be identified.

II. MATERIALS AND METHODS

This study made use of fuzzy multi-criteria decision analysis (FMCDA) in a GIS environment to determine suitable sites for a landfill. A substantial multi-disciplinary evaluation process with multiple sets of criteria was used to identify the best available locations for a new sanitary landfill as illustrated in Figure 1. The final goal was to meet the regulatory requirements and minimize economic, social, and environmental costs associated with the landfill construction, operation, and closure.



NSWMC-EMB: Environmental Management Bureau of the National Solid Waste Management Commission
RA9003: Ecological Solid Waste Management Act of 2000
WLC: Weighted Linear Combination

Figure 1. Landfill site suitability using fuzzy multi-criteria decision analysis (FMCDA) and GIS

2.1 Study Area

Considering that Metro Manila and Quezon City itself cannot site another sanitary landfill, being already too urbanized, the neighboring provinces near the city such as Bulacan and Rizal were considered in this study (see Figure 2).

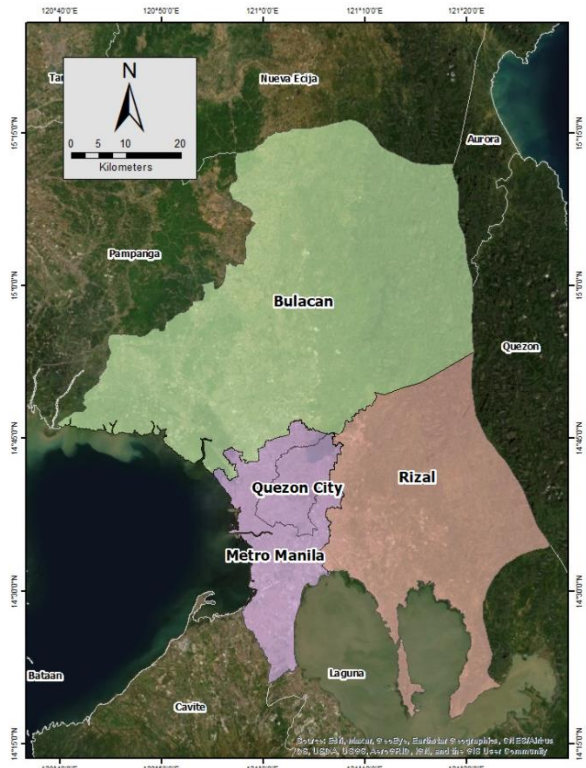


Figure 2. Boundary map of Bulacan, Rizal, Metro Manila, and Quezon City

Quezon City has a total land area of 16,112 hectares and a total population of 2,960,048 as of 2020 [20]. It has the highest population in Metro Manila with an average annual growth rate of 1.58% since 2015. Its waste generation rate as reported by the Environmental Protection and Waste Management Department (EPWMD) in 2013 is 0.88 kg/cap/day [21]. Based on the 2015 population of Quezon City and the average amount of waste disposed, the average waste disposal rate at QCCDF is 0.55 kg/cap/day.

The province of Rizal has a total land area of 118,265 hectares [22]. Since large areas of land are still undisturbed and waiting to be developed [22], it makes a good venue for the possible landfill in terms of land availability, adding to the fact that it sits beside Metro Manila.

The province of Bulacan is proximate and very accessible to Metro Manila, making it one of the candidate provinces to be sited. It has a total land area of 262,500 hectares representing 14% of the total area of Central Luzon [23]. Large areas of land in Bulacan are still undisturbed which also makes it also a good venue for the landfill.

2.2 Selection of Experts

The proposed model for the identification of a potential landfill site was made possible through the integration of economic, social, and environmental factors from RA9003, related literature, and experts' opinions. Group decision-making was utilized in the proposed methodology for landfill site suitability.

A group of fifteen decision-makers who undertook the analysis of factors to be considered could be classified into three fields of expertise: 1) Technical, the seven decision-makers in this field include engineers, academicians, sociologists, and environmental scientists, 2) Regulatory, the two decision-makers in this field are people from the National Solid Waste Management Commission of the Environmental Management Bureau (NSWMC-EMB), and 3) Waste Management, the six decision-makers from this field include the people from the LGUs and landfill operators. It is important to note that the individuals of the group involved in this study, and in every group decision-making, have their own attitudes and motivations in reaching the solution for the common problem.

2.3 Factors and Constraints

From the criteria established in RA 9003, the literature, and the survey done by the experts, fourteen factors were identified and classified into three groups, namely, economic, social, and environmental factors, as follows:

I. Economic Factors
- a. Accessibility from major roadways (RD)
- b. Location from an airport (AP)
- c. Distance from waste generation locations (WG)
- d. Distance from business centers/commercial areas (BC)

II. Social Factors
- a. Location from historical sites (HS)
- b. Location from schools and residential areas (SR)
- c. Distance from fire stations and emergency centers (FS)

III. Environmental Factors
- a. Location from protected and key biodiversity areas (PK)
- b. Distance from any perennial stream, lake, or river (SW)
- c. Distance from fault lines (FL)
- d. Distance from flood hazards (FH)
- e. Soil type (ST)
- f. Depth of groundwater (GW)
- g. Slope (SL)

IV. Constraints

Apart from the factors, constraints such as land use and land area were also considered in this study. Agricultural areas, urban areas, rivers, wetlands, and protected areas were considered unsuitable for landfill siting. A minimum land area was also considered, which was computed from the waste disposal rate of the study area considered.

2.4 Factor Weights and Attributes

Since each factor has a certain degree of importance, the concept of weighting was employed to determine the required level of importance for each factor [24]. The evaluation of these different factors and their corresponding distances required assessment using fuzzy numbers. In the context of FMCDA, the experts were tasked to evaluate each factor by forming fuzzy estimates , either in trapezoidal or triangular form [13]. An absolute rating from 0 to 1 was employed for every factor. Afterward, the estimates provided by each expert, taking account each factor, were aggregated into a collective estimate working with the assumption that the levels of influence of the experts are equal.

2.4.1 Fuzzy Aggregation

Pedrycz, et al. [13] discussed that the collective opinion F_P^C for a particular criterion F_P is commonly obtained by applying the weighted arithmetic mean to combine the estimates provided by each expert $F_P^y, y=1,2,\ldots,v$, into a collective estimate as follows:

$$F_P^C = \sum_{y=1}^{v} w_y F_P^y \tag{3}$$

where $0 \le w_y \le 1$, for $y=1,2,\ldots,v, \sum_{y=1}^{v} w_y = 1$. The sum and the product are implemented in accordance with the addition operation (Equation 4) and the multiplication operation (Equation 5), with each scalar weight w_y per expert represented as a fuzzy singleton.

$$\text{Addition: } (a,b,c,d)+(e,f,g,h)=(a+e,b+f,c+g,d+h) \tag{4}$$

$$\text{Multiplication: } w \times (a,b,c,d)=(a \times w, b \times w, c \times w, d \times w) \tag{5}$$

2.4.2 Ranking and Weighting of Fuzzy Numbers

In the recent years, a number of methods have been proposed based on the distances in general fuzzy number space [25]. The methods that are commonly used require the transformation of fuzzy numbers into real numbers then the resulting numbers are compared. For this study, the method by Abbasbandy and Hajjari [26] in determining the corresponding magnitude of a fuzzy set will be employed. The method requires that the fuzzy numbers be in their parametric form.

For an arbitrary trapezoidal number $u = (x_0, y_0, \sigma, \beta)$, with parametric form $u = \left(\underline{u}(r), \overline{u}(r)\right)$, the magnitude of the trapezoidal number u is defined as

$$\text{Mag}(u) = \frac{1}{2}\left(\int_0^1 \left(\underline{u}(r) + \overline{u}(r) + x_0 + y_0\right) f(r)\ dr\right) \tag{6}$$

Function f(r) can be considered as a weighting function and in this paper, f(r)=r was used. The resulting scalar value, Mag(u), is used to defuzzify and rank the fuzzy numbers involved.

2.5 Data Collection, Standardization, and Analysis

Datasets, both vector and raster, were obtained from different sectors based on availability and suitability. The thematic maps were represented as layers of georeferenced data and constituted the GIS project. These were then transformed on raster grid with cells of 10×10 m2. Since it is required that the values contained in the various criteria map layers be standardized or transformed to comparable units [11], Euclidean distance, normalization and slope analysis were performed. Table 1 gives us the factors and their corresponding analyses for standardization.

Table 1. List of factors and corresponding data, format, source of data, and spatial analysis

FACTORS	DATA	FORMAT	DATA SOURCE	ANALYSIS
Distance from major roads (RD)	Roads	Vector	Open Street Map	Euclidean dist.
Distance from airports (AP)	Airports	Vector	Digitized	Euclidean dist.
Distance from faults (FL)	Faults	Vector	PHIVOLCS[1]	Euclidean dist.
Distance from flood hazard (FH)	Flood hazard	Vector	UP-NOAH[2]	Euclidean dist.
Soil type (ST)	Soil type	Raster	BSWM[3]	Normalization
Distance from protected and KBAs (PK)	Protected areas, KBAs	Vector	DENR[4]/CIP[5]/HF[6]	Euclidean dist.
Slope (SL)	DEM	Raster	UP-NOAH[2]	Slope
Distance from schools and residential areas (SR)	Schools, Residential areas	Vector	Open Street Map	Euclidean dist.
Distance from business centers (BC)	Business centers	Vector	Open Street Map	Euclidean dist.
Distance from historical sites (HS)	Historical sites	Vector	Philippine Heritage Map	Euclidean dist.
Distance from water bodies (SW)	Surface waters	Vector	Open Street Map	Euclidean dist.
Distance from fire stations and emergency centers (FS)	Fire stations	Vector	Open Street Map	Euclidean dist.
Depth to groundwater (GW)	Groundwater wells	Excel	NWRB[7]/LWUA[8]	Kriging
Distance from waste generation locations (WG)	Quezon city boundary	Vector	GADM	Euclidean dist.

[1] Philippine Institute of Volcanology and Seismology
[2 University of the Philippines Nationwide Operational Assessment of Hazards
[3] Bureau of Soils and Water Management
[4] Department of Environmental and Natural Resources
[5] Conservation International Philippines
[6] Haribon Foundation
[7] National Water Resources Board
[8] Local Water Utilities Administration

Buffer distances were provided by the experts for the different factors. The distances were standardized to a continuous scale of suitability from 0 to 1 by fuzzy linear membership functions per expert and are conveyed in the factor maps using GIS. The aggregated score per factor was then obtained as a sum of the products of the cell value (0 to 1) and the experts' level of influence as shown in Equation 7.

$$S_i = \sum_{j=1}^{n} w_j \, v_{ij} \qquad (7)$$

where S_i is the membership score for area i, w_j is the level of influence of expert j , v_{ij} is the standardized value of area i under expert j, and n is the total number of experts. The assumption that the levels of influence of the experts are equal was made. As the sum of these weights is constrained to 1, the final combined estimate was presented on the same scale.

To obtain the suitability map, the computed weights for the various factors from the collective opinion of experts were then aggregated using the same formula in Equation 5, where S_i is the suitability index for area i, w_j is the weight of criterion j , v_{ij} is the standardized value of area i under criterion j, and n is the total number of criteria.

III. RESULTS AND DISCUSSION

3.1 Factor Weights and Attributes

The weights assigned by the experts to the different factors are presented in Table 2. These weights are in the form of either trapezoidal or triangular fuzzy numbers. The collective opinion for every criterion given that the level of influence of the experts is equal, was determined by applying the fuzzy weighted arithmetic mean in Equation 3. The final magnitude of the weight of each criterion was presented in Table 3 using Equation 6. These magnitudes were standardized to obtain a total sum of 1 and were used as the final weight of each criteria.

From the results of the weights, the location from schools and residential areas (SR) along with the distance from surface waters (SW) with scores of 0.084 yielded the highest weights for the landfill site selection factors. These, along with the accessibility to major roadways (RD), constitute the highest values for social, environmental, and economic criteria, respectively. Overall, the depth of the groundwater table (GW) ranks second and has an equivalent weight of 0.083 while the location from fire stations and emergency centers (FS) with an equivalent weight of 0.052 ranks the lowest followed by the distance from historical sites (HS) with an equivalent weight of 0.061. The low score of FS may be attributed to the fact that fire stations and emergency centers can and should be present within the landfill facility during its operational phase, while the low score of HS may be linked with how the experts and the public regard culture and heritage. Comparing these to final weights and ranking given on other studies such as that of Akbari, et al. [16] and Motlagh & Sayadi [10] in Table 4, it can be observed that groundwater is still given high priority along with the surface water and the distance from schools and residential areas. The distance from business centers along with the distance from historic sites are still ranked lower compared to the other factors. In the study by Akbari, et al. [16], however, the distance from major roads has the highest weight, while the distance from a fault line has a low weight.

From the results of the experts' opinion, minimum and maximum distances were also obtained per factor as shown in Table 3. Comparing these to the minimum criteria values mentioned in the IRR of RA 9003 [8], the results of this study are more conservative. These values can be used as basis for landfill siting in the future and can supplement the siting criteria mentioned in RA 9003.

3.2 Suitability Map and Selection of Best Sites

Figure 3 shows the factor maps after they were standardized by the assignment of fuzzy membership based in an evaluation scale of 0 to 1 incorporating the experts' judgement. A landfill suitability map (Figure 4) was then obtained from weighted linear combination of the factors. The final index model was grouped into five categories: unsuitable (0-0.45), low suitability (0.45-0.50), moderate suitability (0.50-0.55), high suitability (0.55-0.6), and very high suitability (0.6 to 1).

In selecting the best sites, the areas with very high suitability (with values ranging from 0.6 to 1) were chosen. These chosen sites were then overlaid with the constraints of land use. Also, to get the suitable landfill size, the formula given by Jaramillo [27] was adopted considering the following: the MSW disposal rate of 0.55kg/cap/day, population growth rate of 1.58%, minimum landfill service life of 10 years, and minimum compaction density of 500kg/m^3 obtained from ADB's study in 2016 [21]. Thus, the required area was set to 80 ha as shown in Table 5. From these, suitable areas were identified as shown in Figure 5. Twenty-six areas or zones were considered possible sites for the landfill.

To ascertain the suitability of these areas, mean factor scores were compared for every area. Table 6 shows the factor scores for every area. It can be observed that all of the areas have low scores (less than 0.5) for both the availability of fire stations and emergency centers and the accessibility from major roads. This is because these locations are at a significant distance away from the metro. The problem with these factors, however, can be resolved by providing means of access and housing fire trucks on-site of the landfill. It can also be noticed that majority of the areas have low scores for the waste generation location factor and the business centers factor. The trend is that as the distance from the metro increases which leads to a lower score, the distance from business centers also increases, which in turn gives us a higher score. However, a number of business centers are now present in the provinces of Bulacan and Rizal because of the rapid urbanization in the country. Considering all the factors for the verification of the area suitability, all of these areas have scores of more than 0.5 for the majority of the factors.

With a view of minimizing the transport costs as necessitated by the Quezon City government, it is an economically sound practice to construct the proposed facility as close to the waste generation area as possible. An optimum distance of 10 km as provided by the experts is considered. Figure 6 shows the nearest suitable sites from Quezon City. These areas, namely 9, 24, and 26, are located in San Jose del Monte, Antipolo, and Rodriquez, respectively. It can be noticed that areas 9 and 26 are near the landfills present in Bulacan and Rizal, namely, the Wacuman sanitary landfill and the Rizal Provincial landfill. These landfills can also possibly site the waste disposed by Quezon City for a short period of time.

Table 2. Weights of different criteria according to experts

Criteria	Experts							
	E1	E2	E3	E4	E5	E6	E7	E8
RD	(0.6, 0.8, 0.9)	(0.5, 0.8, 1)	(0.8, 0.9, 0.95)	(0.5, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.8, 0.9, 1)	(0.6, 0.7, 0.8, 0.9)	(0.75, 0.8, 0.9)
AP	(0.8, 0.9, 1)	(0.8, 0.9, 1)	(0.4, 0.5, 0.6)	(0.6, 0.7, 0.8)	(0.4, 0.7, 0.8)	(0.8, 0.9, 1)	(0.1, 0.11, 0.15)	(0.7, 0.8, 0.9)
WG	(0.7, 0.8, 1)	(0.7, 0.9, 1)	(0.7, 0.8, 0.9)	(0.5, 0.7, 0.9)	(0.7, 0.8, 0.9)	(0.8, 0.9, 1)	(0.45, 0.58, 0.82)	(0.5, 0.55, 0.6)
BC	(0.5, 0.7, 0.8)	(0.8, 0.9, 1)	(0.6, 0.7, 0.8)	(0.6, 0.9, 1)	(0.4, 0.5, 0.6)	(0.4, 0.5, 0.6)	(0.4, 0.5, 0.6)	(0.9, 0.95, 1)
HS	(0.9, 0.93, 1)	(0.7, 0.9, 1)	(0.3, 0.4, 0.5)	(0.5, 0.6, 0.7)	(0.5, 0.7, 0.9)	(0.5, 0.6, 0.7)	(0.5, 0.6, 0.9)	(0.6, 0.7, 0.8)
SR	(0.8, 0.9, 1)	(0.8, 0.9, 1)	(0.6, 0.7, 0.8)	(0.7, 0.8, 0.9)	(0.7, 0.8, 0.9)	(0.8, 0.9, 1)	(0.5, 0.6, 0.7)	(0.9, 0.95, 1)
FS	(0.3, 0.4, 0.5)	(0.7, 0.8, 1)	(0.7, 0.8, 0.9)	(0.6, 0.7, 0.9)	(0.3, 0.4, 0.5)	(0.7, 0.8, 0.9)	(0.4, 0.5, 0.6)	(0.2, 0.3, 0.4)
PK	(0.9, 0.95, 1)	(0.1, 0.5, 1)	(0.8, 0.9, 0.95)	(0.6, 0.7, 0.8)	(0.5, 0.7, 0.8)	(0.7, 0.8, 0.9)	(0.3, 0.35, 0.45)	(0.5, 0.6, 0.7)
SW	(0.8, 0.9, 1)	(0.7, 0.8, 1)	(0.6, 0.7, 0.8)	(0.7, 0.9, 1)	(0.8, 0.9, 1)	(0.8, 0.9, 1)	(0.6, 0.7, 0.75)	(0.9, 0.95, 1)
FL	(0.7, 0.8, 1)	(0.5, 0.6, 1)	(0.3, 0.4, 0.5)	(0.6, 0.8, 0.9)	(0.5, 0.7, 0.9)	(0.8, 0.9, 1)	(0.7, 0.75, 0.8)	(0.1, 0.2, 0.3)
FH	(0.5, 0.7, 1)	(0.7, 0.8, 1)	(0.5, 0.6, 0.8)	(0.8, 0.9, 1)	(0.7, 0.8, 0.9)	(0.8, 0.9, 1)	(0.7, 0.75, 0.8)	(0.4, 0.5, 0.6)
ST	(0.9, 0.99, 1)	(0.5, 0.7, 1)	(0.8, 0.9, 1)	(0.8, 0.9, 1)	(0.8, 0.9, 1)	(0.8, 0.9, 1)	(0.7, 0.8, 0.9)	(0.8, 0.9, 1)
GW	(0.9, 0.98, 1)	(0.5, 0.6, 1)	(0.8, 0.9, 1)	(0.8, 0.9, 1)	(0.8, 0.9, 1)	(0.8, 0.9, 1)	(0.7, 0.75, 0.9)	(0.9, 0.95, 1)
SL	(0.4, 0.5, 0.6)	(0.7, 0.8, 1)	(0.5, 0.6, 0.8)	(0.7, 0.8, 0.9)	(0.6, 0.7, 0.8)	(0.6, 0.7, 0.8)	(0.6, 0.7, 0.8)	(0.8, 0.9, 1)

Criteria	Experts						
	E9	E10	E11	E12	E13	E14	E15
RD	(0.4, 0.5, 0.6)	(0.7, 0.8, 0.9)	(0.4, 0.5, 0.6)	(0.5, 0.6, 0.7, 0.8)	(0.7, 0.8, 0.85, 0.9)	(0.6, 0.7, 0.75)	(0.3, 0.5, 0.7)
AP	(0.7, 0.8, 0.9)	(0.4, 0.5, 0.6, 0.7)	(0.6, 0.7, 0.8)	(0.3, 0.5, 0.6)	(0.75, 0.85, 0.95)	(0.6, 0.75, 0.8)	(0.3, 0.5, 0.7)
WG	(0.3, 0.4, 0.5)	(0.7, 0.8, 0.85)	(0.7, 0.8, 0.9)	(0.3, 0.5, 0.6)	(0.6, 0.75, 0.9)	(0.4, 0.5, 0.7)	(0.5, 0.6, 0.8)
BC	(0.5, 0.6, 0.7, 0.8)	(0.3, 0.4, 0.5, 0.6)	(0.6, 0.7, 0.8)	(0.5, 0.6, 0.7, 0.8)	(0.65, 0.75, 0.85)	(0.4, 0.5, 0.7)	(0.25, 0.35, 0.5)
HS	(0.2, 0.3, 0.4, 0.5)	(0.1, 0.2, 0.3)	(0.4, 0.5, 0.6)	(0.2, 0.3, 0.4)	(0.6, 0.7, 0.8)	(0.7, 0.8, 1)	(0.25, 0.5, 0.7)
SR	(0.7, 0.8, 0.9)	(0.8, 0.95, 1)	(0.6, 0.7, 0.8)	(0.5, 0.6, 0.7, 0.8)	(0.8, 0.9, 0.95, 1)	(0.7, 0.8, 1)	(0.5, 0.8, 0.1)
FS	(0.2, 0.3, 0.4)	(0.05, 0.1, 0.3)	(0.4, 0.5, 0.6)	(0.2, 0.3, 0.4)	(0.8, 0.9, 1)	(0.5, 0.6, 0.65)	(0, 0, 0)
PK	(0.3, 0.4, 0.5)	(0.4, 0.5, 0.6, 0.7)	(0.4, 0.5, 0.6)	(0.4, 0.5, 0.6)	(0.6, 0.7, 0.8, 0.9)	(0.4, 0.5, 0.6)	(0.4, 0.6, 0.8)
SW	(0.8, 0.9, 1)	(0.5, 0.6, 0.7, 0.8)	(0.8, 0.9, 1)	(0.4, 0.5, 0.6)	(0.8, 0.9, 1)	(0.7, 0.8, 1)	(0.4, 0.6, 0.8)
FL	(0.8, 0.9, 1)	(0.3, 0.4, 0.5)	(0.5, 0.6, 0.7)	(0.4, 0.5, 0.6)	(0.7, 0.8, 0.9, 1)	(0.3, 0.4, 0.5)	(0.15, 0.3, 0.5)
FH	(0.7, 0.8, 0.9, 1)	(0.1, 0.2, 0.3)	(0.7, 0.8, 0.9)	(0.5, 0.6, 0.7, 0.8)	(0.6, 0.7, 0.8, 0.9)	(0.5, 0.6, 0.7)	(0.4, 0.6, 0.8)
ST	(0.5, 0.6, 0.7)	(0.6, 0.7, 0.8)	(0.8, 0.9, 1)	(0.6, 0.7, 0.8)	(0.7, 0.8, 0.9, 1)	(0.3, 0.4, 0.5)	(0.15, 0.3, 0.5)
GW	(0.6, 0.7, 0.8)	(0.6, 0.7, 0.8)	(0.8, 0.9, 1)	(0.6, 0.7, 0.8)	(0.75, 0.85, 0.95)	(0.5, 0.6, 0.7)	(0.4, 0.6, 0.8)
SL	(0.5, 0.6, 0.7)	(0.3, 0.4, 0.5, 0.6)	(0.5, 0.6, 0.7)	(0.3, 0.5, 0.6)	(0.7, 0.9, 1)	(0.4, 0.5, 0.6)	(0.15, 0.3, 0.5)

Table 3. Factors Attributes and Weights

Criteria	Fuzzy weights	Magnitude	Weight	Minimum	Maximum
SR	(0.71, 0.81, 0.82, 0.92)	0.806	0.084	3km	-
SW	(0.71, 0.81, 0.82, 0.93)	0.800	0.084	1km	-
GW	(0.72, 0.81, 0.81, 0.93)	0.797	0.083	6.5m	-
ST	(0.67, 0.77, 0.78, 0.89)	0.763	0.08	60%	-
RD	(0.62, 0.75, 0.77, 0.87)	0.732	0.077	500m	4.5km
FH	(0.6, 0.7, 0.72, 0.85)	0.695	0.073	2km	-
WG	(0.54, 0.66, 0.66, 0.79)	0.693	0.073	-	20km
AP	(0.58, 0.69, 0.7, 0.79)	0.675	0.071	3.5km	-
BC	(0.56, 0.67, 0.69, 0.79)	0.646	0.068	4km	-
SL	(0.51, 0.62, 0.63, 0.75)	0.637	0.067	3°	22°
PK	(0.51, 0.63, 0.64, 0.77)	0.620	0.065	2km	-
FL	(0.53, 0.64, 0.65, 0.78)	0.609	0.064	700m	-
HS	(0.5, 0.6, 0.61, 0.74)	0.586	0.061	2.5km	-
FS	(0.44, 0.53, 0.53, 0.65)	0.495	0.052	-	7km

SR: Distance from schools and residential areas; SW: Distance from water bodies; GW: Depth to groundwater; ST: Soil type; RD: Distance from major roads; FH: Distance from flood hazard; WG: Distance from waste generation locations; AP: Distance from airports; BC: Distance from business centers; SL: Slope; PK: Distance from protected and KBAs; FL: Distance from faults; HS: Distance from historical sites; FS: Distance from fire stations and emergency centers

Table 4. Factors Attributes and Weights

Criteria	Weight		Ranking		Minimum Value	
	This study	Akbari, et al. (2008)	This study	Motlagh, et al. (2015)	This study	IRR of RA 9003
SR	0.806	0.75	1	4	3km	-
SW	0.80	0.65	1	3	1km	50m
GW	0.797	-	2	1	6.5m	-
ST	0.763	0.55	3	4	60%	-
RD	0.732	0.9	4	5	500m	-
FH	0.695	-	5	-	2km	-
WG	0.693	-	5	-	-	-
AP	0.675	0.45	6	6	3.5km	2km
BC	0.646	-	7	9	4km	-
SL	0.637	0.8	8	8	3	-
PK	0.62	-	9	2	2km	-
FL	0.609	0.35	10	-	700m	75m
HS	0.586	-	11	7	2.5km	-
FS	0.495	-	12	-	-	-
Operational life	-	-	-	-	10 years	5 years

SR: Distance from schools and residential areas; SW: Distance from water bodies; GW: Depth to groundwater; ST: Soil type; RD: Distance from major roads; FH: Distance from flood hazard; WG: Distance from waste generation locations; AP: Distance from airports; BC: Distance from business centers; SL: Slope; PK: Distance from protected and KBAs; FL: Distance from faults; HS: Distance from historical sites; FS: Distance from fire stations and emergency centers

Table 5. Calculation of Required Landfill Area

No.	Description	Value
Q1	Total waste to be filled (10^3 kg)	6,331,489
Q2	Density of waste compacted (kg/m^3)	500
Q3	Landfill volume required (m^3) (Q1/Q2)	12,662,978
Q4	Cover rate	10%
Q5	Total landfill volume (waste + cover) (m^3)	13,929,276
Q6	Landfill depth (m)	20
Q7	Required landfill net area (m^2) (Q5/Q6)	696,464
Q8	15% Extra area required for operation facilities	104,470
	(m^2) (15% Q7)	
Q9	Total landfill area (m^2) (Q7 + Q8)	800,933
Q10	Total landfill area (ha)	80

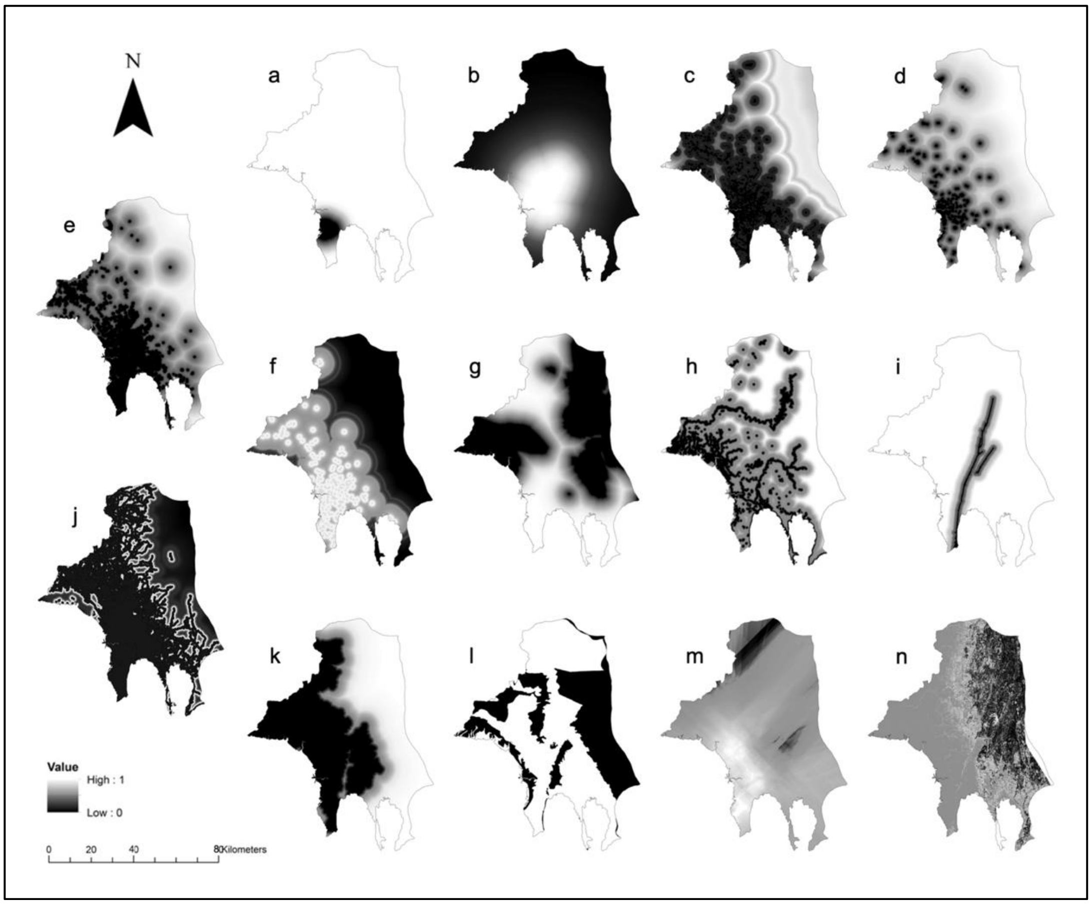


Figure 3. Fuzzy standardized maps for the factors: (a) Distance from airports, (b) Distance from waste generation locations, (c) Distance from business centers, (d) Distance from historical sites, (e) Distance from schools and residential areas, (f) Distance from fire stations and emergency centers, (g) Distance from protected and KBAs, (h) Distance from water bodies, (i) Distance from faults, (j) Distance from major roads, (k) Distance from flood hazard, (l) Soil type, (m) Depth to groundwater, (n) Slope

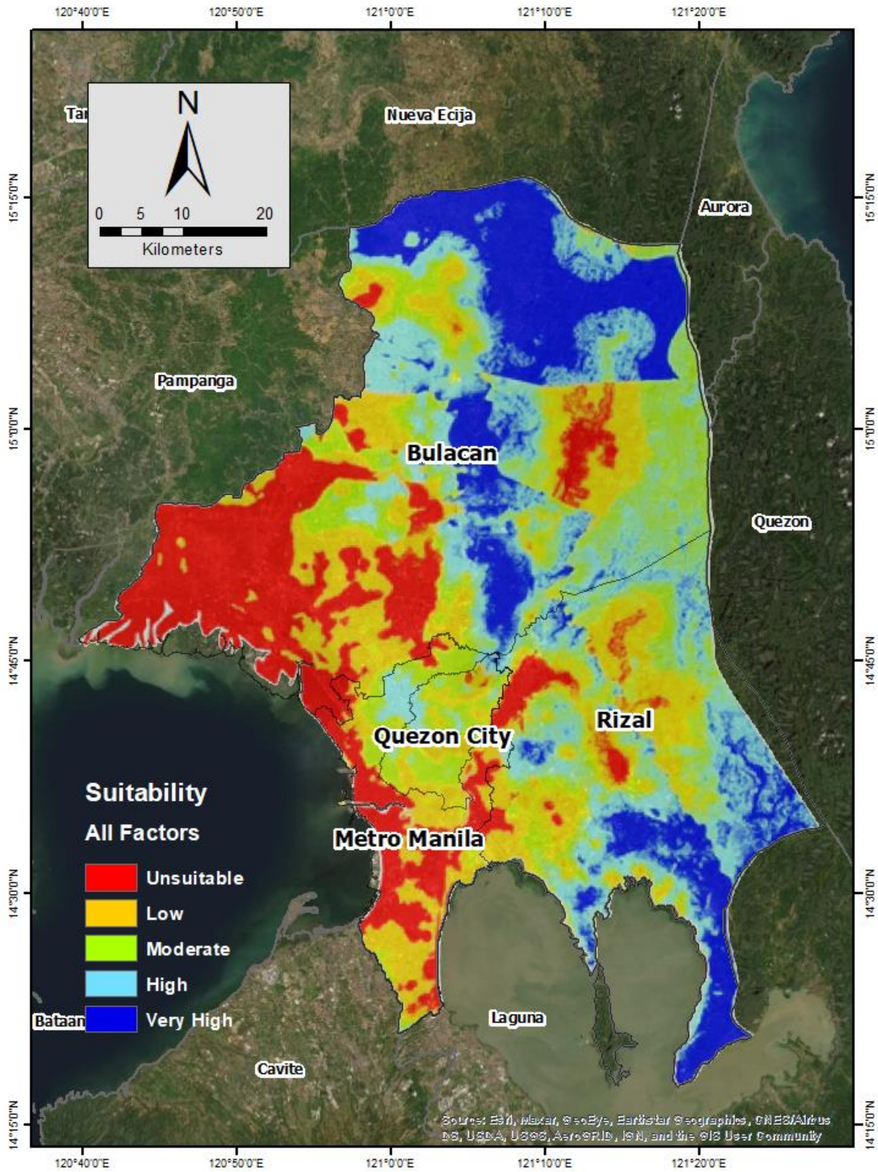


Figure 4. Landfill Suitability Map with values 0-0.45 as unsuitable, values 0.45-0.50 as low suitability, values 0.50-0.55 as moderate suitability, values 0.55-0.6 as high suitability, and values 0.6 to 1 as very high suitability

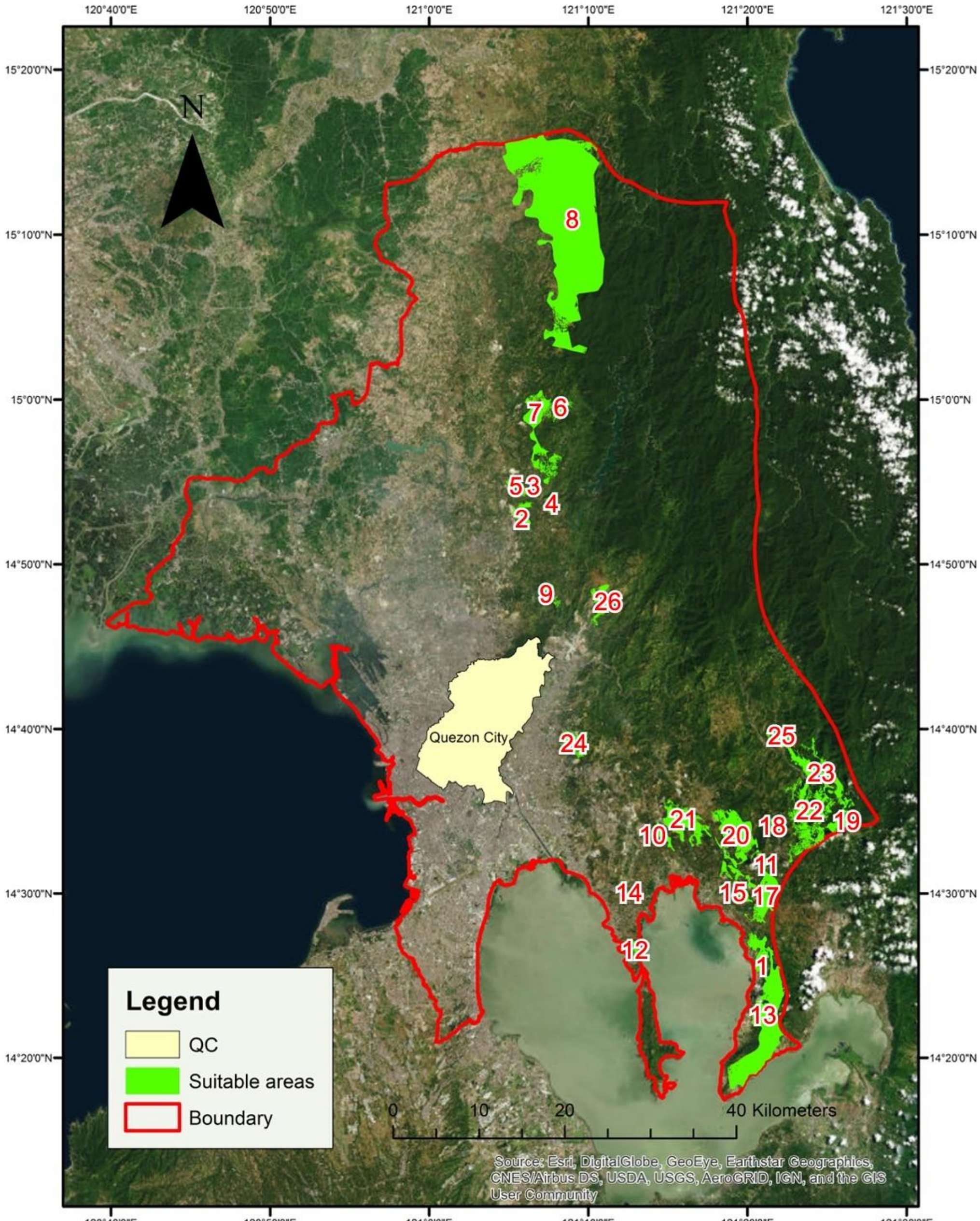


Figure 5. Twenty-six suitable landfill sites for Quezon City's solid waste with >80ha area requirement

Table 6. Factor scores per suitable area

Number	Area (Sq.m.)	HS	GW	FH	FL	FS	BC	WG
1	1,172,420	0.85	0.947	1	0.909	0.184	0.248	0.058
2	1,889,480	0.782	0.942	0.568	0.909	0.416	0.077	0.404
3	851,138	0.783	0.941	0.61	0.909	0.394	0.11	0.335
4	1,067,350	0.59	0.942	0.825	0.856	0.364	0.055	0.336
5	1,603,580	0.817	0.942	0.654	0.909	0.363	0.121	0.274
6	2,122,290	0.925	0.934	0.959	0.909	0.067	0.546	0.124
7	12,665,400	0.878	0.935	0.923	0.909	0.111	0.39	0.164
8	138,560,000	0.913	0.897	0.933	0.909	0.067	0.511	0.015
9	2,015,450	0.778	0.936	0.287	0.691	0.374	0.332	0.911
10	1,721,130	0.709	0.95	0.778	0.909	0.394	0.229	0.258
11	1,768,630	0.731	0.949	0.981	0.909	0.388	0.065	0.103
12	928,886	0.862	0.942	0.968	0.909	0.163	0.136	0.179
13	36,586,400	0.699	0.944	1	0.909	0.12	0.278	0.044
14	871,676	0.634	0.947	0.906	0.909	0.292	0.225	0.268
15	1,772,180	0.624	0.947	0.985	0.909	0.408	0.068	0.094
16	950,189	0.655	0.948	0.972	0.909	0.4	0.07	0.127
17	9,924,240	0.77	0.949	0.992	0.909	0.344	0.105	0.073
18	925,577	0.902	0.949	0.976	0.909	0.12	0.318	0.079
19	3,463,670	0.904	0.95	1	0.909	0.067	0.512	0.048
20	14,568,700	0.841	0.951	0.962	0.909	0.225	0.164	0.126
21	11,536,500	0.77	0.949	0.844	0.909	0.307	0.253	0.217
22	17,318,300	0.92	0.949	0.99	0.909	0.08	0.469	0.062
23	9,763,580	0.968	0.949	0.991	0.909	0.067	0.535	0.064
24	4,350,060	0.815	0.938	0.003	0.835	0.425	0.165	0.876
25	2,961,230	0.95	0.95	0.973	0.909	0.067	0.52	0.106
26	4,338,440	0.836	0.93	0.16	0.724	0.195	0.375	0.752

Number	SW	ST	SL	SR	RD	PK	AP
1	0.589	1	0.553	0.4	0.338	1	1
2	0.562	1	0.621	0.642	0.214	0.682	1
3	0.301	1	0.678	0.682	0.38	0.641	1
4	0.476	1	0.717	0.786	0.27	0.33	1
5	0.425	1	0.657	0.636	0.301	0.694	1
6	0.983	0	0.623	0.722	0.375	0.529	1
7	0.916	0.781	0.505	0.581	0.253	0.582	1
8	0.836	0.991	0.436	0.827	0.221	0.51	1
9	0.634	1	0.643	0.49	0.094	0.795	1
10	0.689	1	0.609	0.462	0.148	0.669	1
11	0.687	1	0.623	0.418	0.147	0.888	1
12	0.357	1	0.66	0.477	0.136	1	1
13	0.595	0.995	0.404	0.722	0.254	0.999	1
14	0.556	1	0.587	0.305	0.096	0.975	1
15	0.567	1	0.643	0.391	0.124	0.947	1
16	0.567	1	0.677	0.391	0.267	0.83	1
17	0.901	0.997	0.561	0.462	0.139	0.945	1
18	1	0	0.73	0.565	0.425	0.652	1
19	1	0	0.585	0.874	0.38	0.544	1
20	0.973	0.999	0.462	0.425	0.257	0.476	1
21	0.868	1	0.621	0.533	0.13	0.445	1
22	1	0	0.53	0.716	0.248	0.831	1
23	1	0	0.493	0.784	0.279	0.759	1
24	0.715	1	0.662	0.372	0.177	0.752	1
25	1	0	0.558	0.734	0.308	0.633	1
26	0.847	0.995	0.337	0.506	0.381	0.618	1

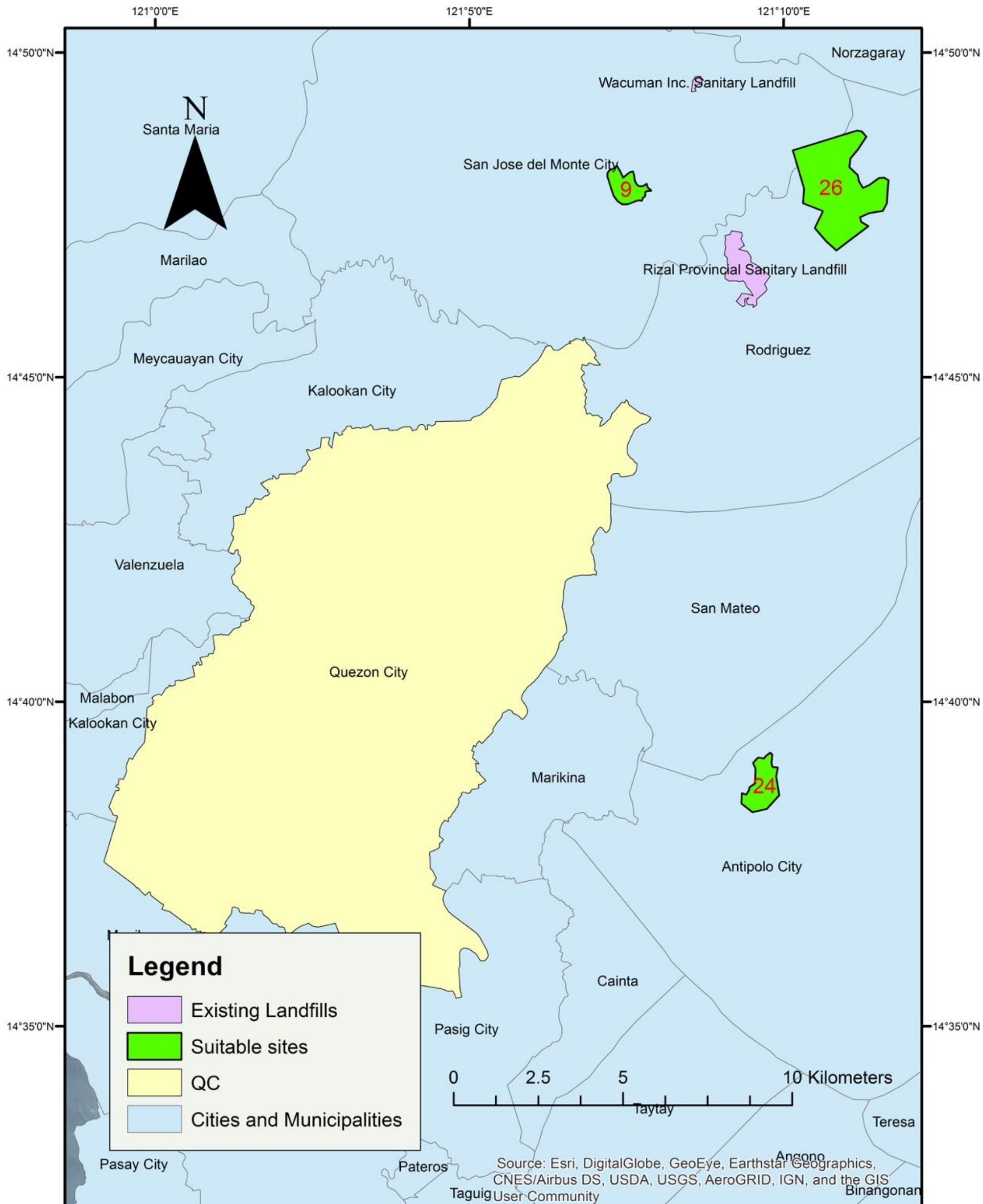


Figure 6. Nearest suitable landfill sites for Quezon City's solid waste

IV. CONCLUSION AND RECOMMENDATIONS

Landfill site suitability is a multidisciplinary and complicated process. Therefore, careful consideration of all factors from environmental, social, and economic is required. This study has demonstrated a methodology to select suitable sites for landfill siting with the use of FMCDA in a GIS environment considering Quezon City's waste. The development of the method is based on achieving goals to minimize the negative impacts posed by the construction, operation, and closure of a landfill site.

Through consultations with experts in the technical, regulatory, and waste management fields, legislatures, and related literature, a set of criteria was determined. However, limitations on data availability should always be considered. Subsequently, factor weights accompanied by their corresponding attributes were also determined to supplement the limitations of RA 9003. In GIS, the factors were standardized and weighted in terms of their importance using fuzzy estimates provided by the experts. Using WLC, the standardized maps were then combined along with the several constraints imposed in this study. As a result, a map of suitable areas was presented. Factor scores per suitable area can also be readily obtained to aid in the ranking of the suitable sites.

It was demonstrated that the integrated method of using FMCDA in the GIS environment can be implemented easily and considered effective for landfill site selection due to its capacity of handling large volume of multiple datasets in a time-efficient manner (Kao and Lin, 1996). Using this, city planners and decision makers can then be provided with a useful tool for decision making.

In future studies, other factors, such as wind direction, cost of land acquisition and cost of development and operation of the facility, can also be considered in selecting the best site. Additionally, the selected sites should be evaluated in terms of land ownership. If all these other factors are considered, there would be a significant reduction in both the cost and time associated with detailed site investigations [29]. It should also be noted that although the methodology presented can effectively assist the landfill site selection, final field inspections are still needed for added verification.

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