Science World Journal Vol. 17(No 3) 2022
www.scienceworldjournal.org
ISSN: 1597-6343 (Online), ISSN: 2756-391X (Print)
Published by Faculty of Science, Kaduna State University

Full Length Research Article

GEOSPATIAL METHOD OF SITING SUSTAINABLE SANITARY LANDFILL IN JOHOR MALAYSIA

[1]H.I. Mohammed, [2]Z. Majid and *[3]Y.B. Yamusa

[1]Department of Geography, Faculty of Science, Kaduna State University, Nigeria
[2]Department of Geoinformation, Faculty of Built Environment and Surveying, Universiti Teknologi Malaysia
[3]Department of Civil Engineering, School of Engineering Technology, Nuhu Bamalli Polytechnic, Zaria, Nigeria

*Corresponding Author Email Address: yamusabello@gmail.com

ABSTRACT
To obtain an accurate and precise result in any sanitary landfill siting study, one must be able to identify important criteria which are very crucial and challenging in geoinformatics. The level of importance of each criterion varies from one region or country to another. In this research, intensive literature review was carried out to extract the most important criteria to be used in siting sanitary landfill sites in the study area in accordance with local and international guidelines. Three main criteria were identified: environmental, social, and economic. They were divided into thirteen sub-criteria; water bodies, geology, soils, elevation, slope, residential areas, archeological sites, airports, population, roads, railways, infrastructures, and land use and land cover which were used to produce the map of the best potential sites. Ranking and weighing of each criterion was done using AHP pair-wise comparison matrix and normalization of the matrix to get the weight of each criteria. The study revealed that, 54% of the study area were unsuitable areas for sanitary landfill site, 12% less suitable, 21% suitable and 13% most suitable. Three most suitable potential sites were identified among the various sites from the class of most suitable sites in the final map and were validated using the satellite imagery of the study area via Google Earth PRO and field survey. This method can be an advanced alternative to the existing methodologies for selecting relevant criteria in siting sanitary landfill and for long-term planning of solid waste management.

Keywords: Geographic information system, Analytical hierarchy process, Solid waste management

INTRODUCTION

Johor is among the states in Malaysia developing at a speedy pace. It has a population of about 1.5 million by 2010 statistics and expected to be 2.8 million in 2025 (Mohammed *et al.*, 2018a). This means that an increase in the solid waste generation is expected. Unfortunately, record shows that by 2010, Johor had terminated 21 landfills, and 15 are still operating with only 1 among them being sanitary landfill, and the rest are either open or controlled landfills (Samsudina and Dona, 2013). This is causing great concerns as one sanitary landfill cannot accommodate the waste generation for long, except with an alternative for expansion. These uncontrolled landfills have repercussion leading to unpleasant views, leachate generation, water contamination and costlier waste management (Mohammed *et al.*, 2019a). These challenges could be overcome by creating new sanitary landfill sites.

The United State is one of the countries that saw the earliest changes in the development of sanitary landfills in the 20th century through the process of depositing solid waste in layers, compacting, as well as making sure it is often covered with soil. Several countries (e.g. Canada, United States, United Kingdom, Sweden, Australia, and Malaysia) have adopted governmental regulations involving the selection, design, and monitoring of modern landfills to avoid negative social and environmental impacts (Scott *et al.*, 2005). Landfill site selection operation can involve the advantages of geospatial technology, namely remote sensing, Geographical Information Systems (GIS), Global Positioning System (GPS) and Multi-Criteria Decision-Making Methods (MCDM). Hence, they serve as powerful tools for addressing problems arising from landfill site selection (Mohammed *et al.*, 2019b). Remote sensing has a great potential to extract earth surface features such as roads, rivers, and vegetation, as well as providing a detailed land cover and land use map from satellite images (Wasige *et al.*, 2013). GIS allows the analyst to efficiently utilise data from various sources to produce detailed models to identify potential places. Multi-Criteria Decision-Making Analysis (MCDA) is often used to handle complex information in very large quantities, especially in this area of research where criteria maps weightings are used together with GIS to recognize the most suitable landfill site.

Planned sites for sanitary landfills must be first evaluated and measured in detail to determine its social, environmental, economic, and geotechnical attributes in term of subsoil and geological formations, which consist of rock types, tectonic properties, groundwater level depth, etc. (Önal *et al.*, 2013). The most problematic aspects of the disposal process of municipal solid waste is the site selection issue (Kemal Korucu and Erdagi, 2012; Mohammed *et al.*, 2017; Mohammed *et al.*, 2018b). Due to the many factors required when identifying landfills, this makes it become a very complex process (Önüt and Soner, 2008). These factors can be referred to as social, environmental, geomorphological, economic, geological, hydrological, and geotechnical. In many developing countries, the required data is collected via traditional methods, which are tedious and time consuming, or old existing data is used (Mohamed and Plante, 2002). According to Chabuk *et al.* (2016), there is a need for waste disposal sites in the surrounding area to preserve the biophysical environment and ecology. Similarly, other factors that must also be considered are the factors associated with the economy, which comprise the cost of acquiring the land together with both developmental and operational costs (Yesilnacar and Cetin, 2008). Likewise, when protecting the environment as well as public health while making sure the need for better sustainability features in term of quality of life, the selection of landfill sites is seen as a fundamental step when it comes to ultimate waste disposal practices. In terms of the preliminary landfill process, the required successive steps are determined by proper landfill site selection. To ensure undesirable long-term effects are avoided, it is necessary to implement landfill siting. Therefore, landfill sites should be carefully selected through the recommendations provided by environmental agencies (Ahmad *et al.*, 2011).

Furthermore, it can be observed that landfill siting analysis typically requires evaluating various rules, factors, constraints, and numerous spatial data which modern GIS, although capable of rapidly processing a massive amount of spatial data, lacks the ability to locate an optimal site when compactness and other factors are simultaneously evaluated. Previously developed GIS-based model could not be applied to resolve this inability for irregularly shaped spatial data. Therefore, an enhanced spatial siting model is developed herein for general spatial data with the integration of both GIS, remote sensing, and multi-criteria evaluation methods. The study area (Johor Bahru) was used to demonstrate the applicability of the developed model.

MATERIALS AND METHODS

This study covers Johor Bahru (JB). It lies within latitude 1° 29' 0" N and longitude 103° 44' 0" E. JB was chosen in this study as it is one of the rapid developing area in Johor state because of its proximity to Singapore. This has contributed to the increasing amount of solid waste generation. Therefore, selecting sustainable sanitary landfill site in this area is needed because the existing sanitary landfill might not accommodate the waste produced eventually. Figure 1 shows the map of the study area.

Figure 1. Map of the study area

Model Development

To determine the best potential location for sanitary landfill in the study area, the GIS and its spatial analysis tools, integrated with MCDA, and geotechnical analysis were used to this aim according to the recommended criteria. The flow chart in this research is presented in Figure 2. The trend of the developed hybrid model in this research is presented as the conceptual hybrid model for sanitary landfill identification process (Figure 2). The aim of the study is to develop this hybrid model for the best sanitary landfill siting. Thus, a set of important sanitary landfill siting criteria were determined as explained earlier in this chapter in which three main criteria that include environmental, social, and economic were identified and further divided into thirteen sub-criteria. In addition, the projection of all the thematic map layers used were converted into Kertau RSO projection system and ArcGIS was used to prepare all sub-criteria map layers using the Euclidean Distance analysis because it provides closest source of each cell in a raster output format and reclassification was also performed. Furthermore, the Analytical Hierarchy Process (AHP) method of weight determination was applied using the AHP template in excel sheet and the Map Algebra tool was used to apply the weight to each criterion and finally arriving at final potential sanitary sites map.

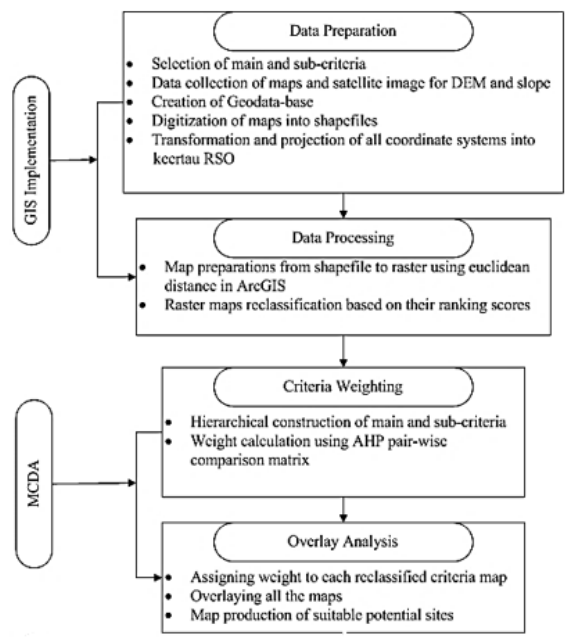

Figure 2. Flow chart of the study

The DEM is known as a continuous way of digital representation of earth's topography (Hengl *et al.*, 2003). It is an important input layer in sanitary landfill siting. The DEM of study area was created using ASTER GDEM imagery with 30m spatial resolution. Figure 3 shows the study area elevation map.

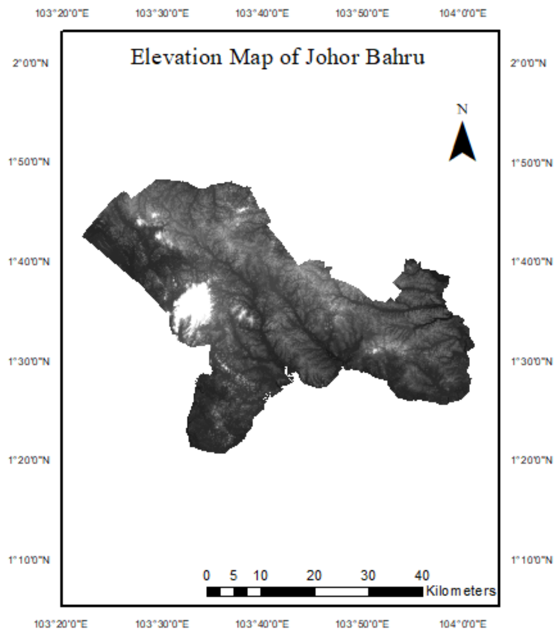

Figure 3. Elevation map

MCDA Method using AHP
AHP is a well-structured mathematical and psychological method of organizing and analyzing complex decisions. Presently, AHP method remained widely used by decision-makers and researchers in understanding of problems and choosing the one which is best for their goal (Madurika and Hemakumara, 2015; Djokanović *et al.*, 2016; Khademalhoseiny *et al.*, 2017; Ghobadi *et al.*, 2017). In this method, the problems are broken down into a hierarchical order making it easier to be analyzed independently (Chen *et al.*, 2013). After the construction of the hierarchy, systematically evaluation of the different criterion by comparing each one to the other with respect to their impact or effect on one another.

Decision-Making Tree
The decision tree is aimed at selecting appropriate site for sustainable sanitary landfill. This is because of its flexible strategy gives rise to achieving a specific goal. The structure of the hierarchy employed for the decision making of this research is displayed in Figure 4 consisting of three main criteria and thirteen sub-criteria used in this research.

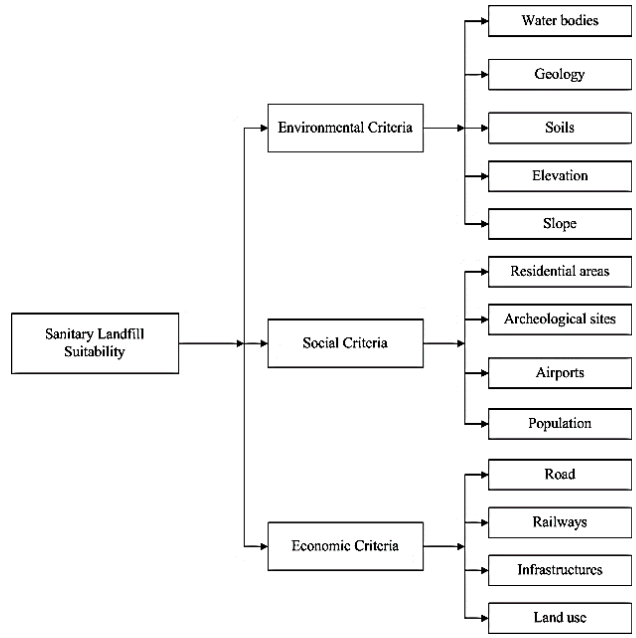

Figure 4. Hierarchical diagram of decision-making tree

Pairwise Comparison
Pairwise comparison is then applied which enable the comparison of these criterion used and the relative importance weight of each criteria was derived and assigned to all the criteria. This is been measured according to a numerical scale of 1 to 9 depending on the level of its significance from equal importance to extreme importance as shown in Table 1. This method breaks down the decision making process as it permit the decision-makers to deal with each criteria separately by comparing with the others (Khodaparast *et al.*, 2018).

Table 1. Pair wise comparison scale

Intensity of importance	Definition
1	Equal importance
2	Equal to moderately importance
3	Moderate importance
4	Moderate to strong importance
5	Strong importance
6	Strong to very strong importance
7	Very strong importance
8	Very strong to extreme importance
9	Extreme importance

The importance of each criterion may vary from one another. The next step in AHP after structuring the pair-wise comparison scale is weighting of the criterion. This is because when siting a sanitary landfill not all the criteria are of equal importance. Therefore, pairwise comparison is necessary to compute for the relative importance weight the criteria used by applying the Saaty numerical scale of 1 to 9.

RESULTS AND DISCUSSION

GIS Analysis

The map layers were generated using remote sensing and GIS techniques. The DEM was derived from the ASTER GDEM satellite imagery. These maps were reclassified based on landfill site selection literatures using the grading scale of 0-10. Where 0 means unsuitable areas and 10 means most suitable areas. Thus, all reclassified map layers in this study were divided into four categories which are “unsuitable”, “less suitable”, “suitable”, and “most suitable”. Figure 5 shows the reclassified maps of the criteria.

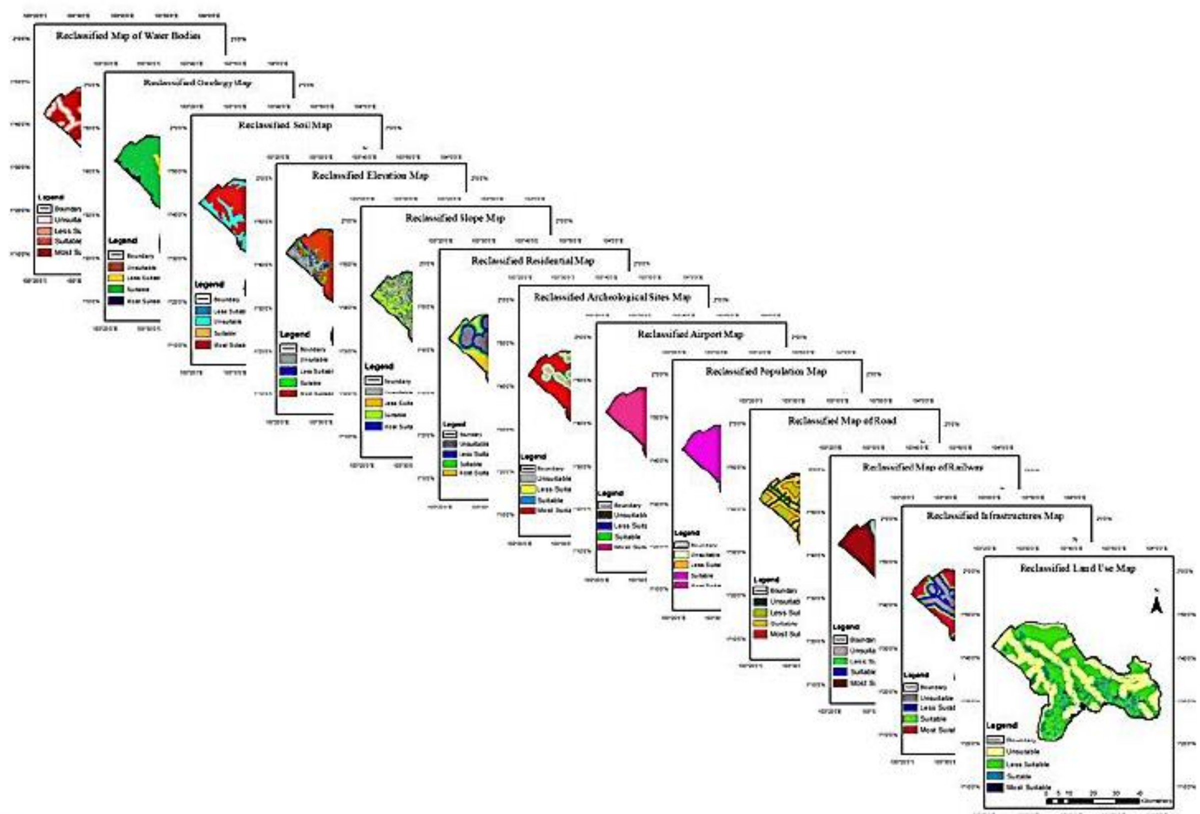

Figure 5. Reclassified maps

The first stage in AHP is developing hierarchy structure in order to solve the complex decision problem. After this, determination of level of importance of criteria is done through pairwise comparison matrix. The relationship between each criterion is compared to the others which is believed to provide easier ranking. In addition, these weights have influence on the determination of suitable sanitary landfill sites in the study area. According to the judgement from the developed pair wise comparison matrix for the thirteen criteria used for this study is reiterated in Table 2. It can be noticed that road is as equal important as infrastructure. This is because siting a sanitary landfill near infrastructure poses similar risk to road.

Table 2. Pair wise comparison matrix

Criteria	Residential	Water bodies	Geology	Soils	Land use	Slope	Elevation	Road	Infrastructure	Airport	Population	Archeological	Railway
Residential	1	3	4	3	5	5	7	7	5	7	2	5	8
Water bodies	1/3	1	2	3	5	4	5	5	4	5	2	5	9
Geology	1/4	1/2	1	2	3	3	4	4	3	4	4	3	6
Soils	1/3	1/3	1/2	1	3	3	1	3	4	4	4	3	5
Land use	1/5	1/5	1/3	1/3	1	2	3	3	2	3	2	2	4
Slope	1/5	1/4	1/3	1/3	1/2	1	2	2	2	2	3	2	3
Elevation	1/7	1/5	1/4	1	1/3	1/2	1	2	3	2	2	3	2
Road	1/7	1/5	1/4	1/3	1/3	1/2	1/2	1	1	2	2	2	2
Infrastructure	1/5	1/4	1/3	1/4	1/2	1/2	1/3	1	1	3	3	2	3
Airport	1/7	1/5	1/4	1/4	1/3	1/2	1/2	1/2	1/3	1	2	3	2
Population	1/2	1/2	1/4	1/4	1/2	1/3	1/2	1/2	1/3	1/2	1	2	2
Archeological	1/5	1/5	1/3	1/3	/2	1/2	1/3	1/2	1/2	1/3	1/2	1	2
Railway	1/8	1/9	1/6	1/5	1/4	1/3	1/2	1/2	1/3	1/2	1/2	1/2	1
Sum	3.77	6.94	9.99	12.82	20.25	21.17	25.67	30	26.50	34.33	28	33.50	49

Next, was normalization of the matrix in order to calculate the weight of each criterion. Table 3 shows the normalization matrix, while Table 4.3 shows the calculated weight and percentage of each criterion used in this study, respectively. The weight results obtained for each criterion was further used in the GIS environment to produce the potential sanitary landfill sites.

Table 3. Normalization matrix

Criteria	Residential	Water bodies	Geology	Soils	Land use	Slope	Elevation	Road	Infrastructure	Airport	Population	Archeological	Railway
Residential	0.265	0.432	0.400	0.244	0.246	0.236	0.272	0.233	0.188	0.203	0.071	0.149	0.163
Water bodies	0.088	0.144	0.200	0.244	0.246	0.188	0.194	0.166	0.150	0.145	0.071	0.149	0.183
Geology	0.066	0.072	0.100	0.162	0.148	0.141	0.155	0.133	0.113	0.116	0.142	0.089	0.122
Soils	0.087	0.047	0.050	0.081	0.148	0.141	0.038	0.100	0.150	0.116	0.142	0.089	0.102
Land use	0.053	0.028	0.033	0.027	0.049	0.094	0.116	0.100	0.075	0.087	0.071	0.059	0.081
Slope	0.053	0.036	0.033	0.027	0.024	0.047	0.077	0.066	0.075	0.058	0.107	0.059	0.061
Elevation	0.037	0.028	0.025	0.081	0.016	0.023	0.038	0.066	0.113	0.058	0.071	0.089	0.040
Road	0.037	0.028	0.025	0.027	0.016	0.023	0.019	0.033	0.037	0.058	0.071	0.059	0.040
Infrastructure	0.053	0.036	0.033	0.020	0.024	0.023	0.012	0.033	0.037	0.087	0.107	0.059	0.061
Airport	0.037	0.028	0.025	0.020	0.016	0.023	0.019	0.016	0.012	0.029	0.071	0.089	0.040
Population	0.132	0.072	0.025	0.020	0.024	0.015	0.019	0.016	0.012	0.014	0.035	0.059	0.040
Archeological	0.053	0.028	0.033	0.027	0.024	0.023	0.012	0.016	0.018	0.009	0.017	0.029	0.040
Railway	0.033	0.015	0.016	0.016	0.012	0.015	0.019	0.016	0.012	0.014	0.017	0.014	0.020

According to the results of the criteria weight as shown in Table 4, more importance was given to residential areas (0.239) while railway criteria has the least importance with weight of 0.018. This is because of the strict rules and regulations governing the prohibition of sanitary landfill near the residential areas.

Table 4. Criteria weight and percentage

Criteria	Weight	Percentage
Residential	0.239	23.9%
Water bodies	0.168	16.8%
Geology	0.121	12.1%
Soils	0.099	9.9%
Land use	0.067	6.7%
Slope	0.056	5.6%
Elevation	0.054	5.4%
Road	0.036	3.6%
Infrastructure	0.046	4.6%
Airport	0.033	3.3%
Population	0.038	3.8%
Archaeological	0.025	2.5%
Railway	0.018	1.8%
Total	1	100%

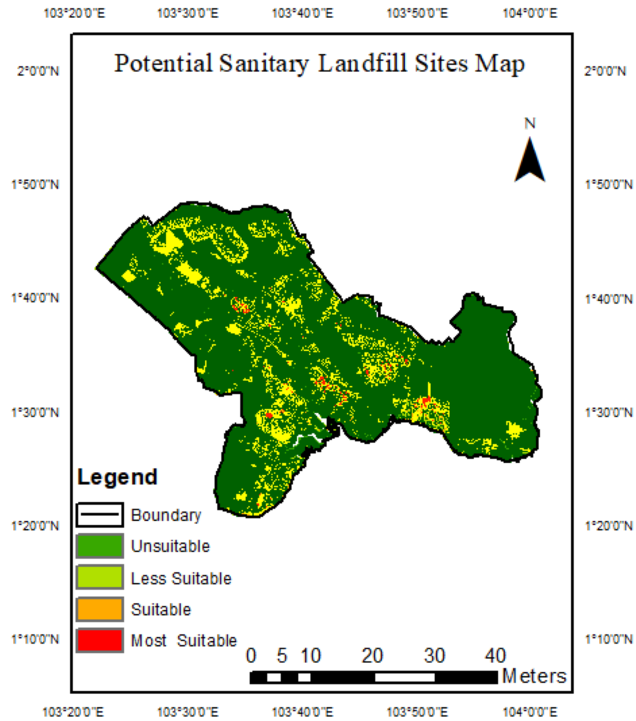

Figure 6. Potential sanitary landfill sites map

Final Potential Sites Map for Sanitary Landfill
In this research, the raster calculator operation was performed in Map Algebra tool to identify the potential sites map. This was carried out by overlaying all the criteria weights assigned to each map layer and the final potential sites map was produced based on this analysis. The potential map of the sanitary landfill sites is displayed in Figure 6.

The map shows the distribution of the selected areas based on suitability where the most suitable are considered the highest priority sites. The legend was used to provide visual clarity of the map showing the various classes of suitability. From the result of this map, it was found that most of the areas are unsuitable with the highest total of the study area, followed by less suitable, suitable and most suitable.

Furthermore, to get the most suitable sites, the potential sites map was then imported to the condition toolset in the Spatial Analyst tool in ArcGIS to identify the most suitable or highest priority sites for determination of best sites for sustainable sanitary landfill as shown in Figure 7.

Science World Journal Vol. 17(No 3) 2022
www.scienceworldjournal.org
ISSN: 1597-6343 (Online), ISSN: 2756-391X (Print)
Published by Faculty of Science, Kaduna State University

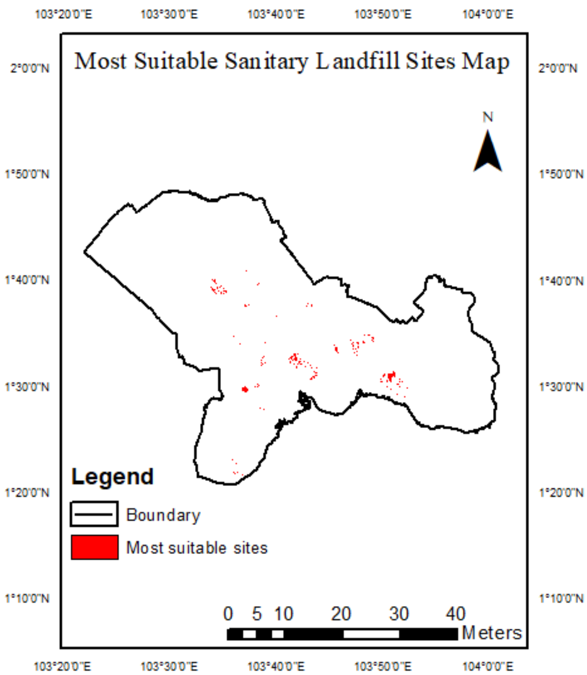

Figure 7. Most suitable sites map after filtering

Best Potential Sites Map
From the most suitable sites, the best potential sites were identified by filtering the most suitable sanitary landfill layer. Thus, the output layer which is in raster format was converted to into vector and then selecting the areas that does not have an intersection with water bodies. Based on expert's judgment using the AHP criteria weighting and GIS analysis, three candidate sites appeared to be the best from environmental, economic, and social perspectives. These sites have fulfilled the requirements for sanitary landfill siting with a distance of at least 1000m away from roads, 1500m away from residential areas, and far away from public and educational facilities. These three sites as displayed in Figure 8 were used to further accomplish the remaining objectives of this research.

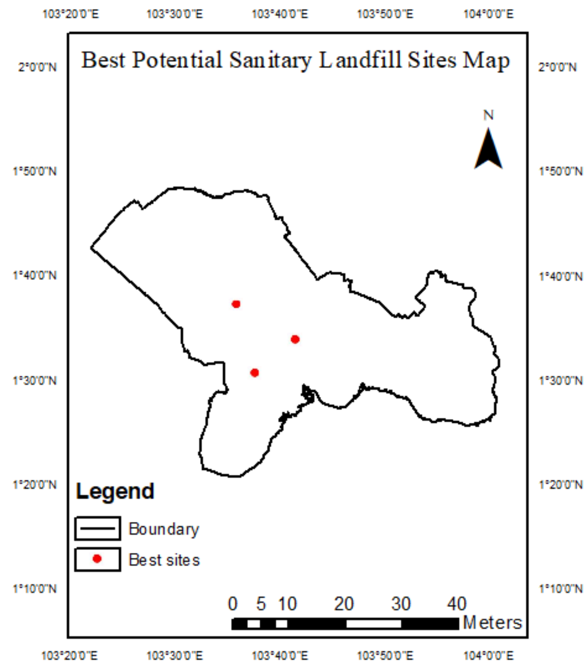

Figure 8. Best potential sanitary landfill sites map

Validation of Potential Sites for Sustainable Sanitary Landfill
To assess the accuracy of the three selected sites from the results generated in this study, a validation process was conducted in two ways which are:

1) Converting the best potential sanitary landfill site map into Keyhole Markup Language (KML) file overlaying it on the satellite image map of the study area using Google Earth PRO.
2) Identification and collection of the coordinates of these sites from the Google Earth PRO as displayed in Table 5 and Figure 9 for field investigation to determine their accuracy and precision.

The three best potential sites are denoted site A, B, and C shown in Figures 10, 11, and 12, respectively.

Table 5. Location of best potential sites

S/No	Best potential site	Latitude	Longitude
1	Best potential site A	1°35'45.62"N	103°38'12.00"E
2	Best potential site B	1°32'14.19"N	103°38'34.56"E
3	Best potential site C	1°33'7.37"N	103°41'34.87"E

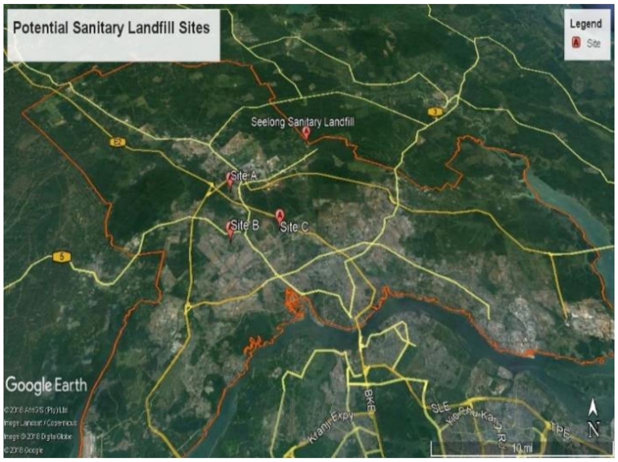

Figure 9. Best potential sanitary landfill sites map using Google Earth

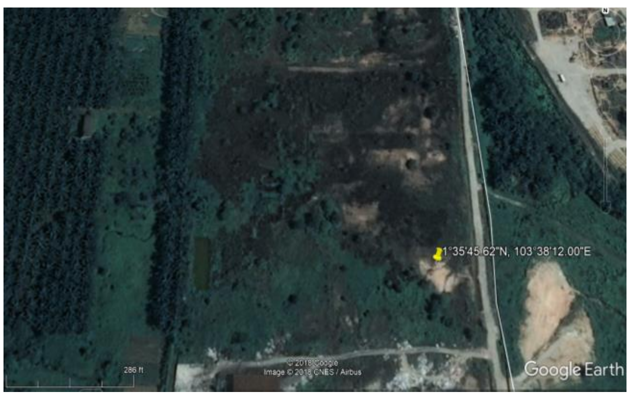

Figure 10. Best potential sanitary landfill site map A

Figure 11. Best potential sanitary landfill sites map B

Figure 12. Best potential sanitary landfill sites map C

Conclusion

To obtain an accurate and precise result in any sanitary landfill siting study, one must be able to identify important criteria which are very crucial and challenging. The level of importance of each criterion varies from one region or country to another. In this research, intensive literature review was carried out to extract the most important criteria to be used in siting sanitary landfill sites in the study area in accordance with local and international guidelines. Three main criteria were identified: environmental, social, and economic. They were divided into thirteen sub-criteria; water bodies, geology, soils, elevation, slope, residential areas, archeological sites, airports, population, roads, railways, infrastructures, and land use/land cover which were used to produce the map of the best potential sites.

The GIS and MCDA (using AHP) were applied in this study for assessing the possible best potential sites for sanitary landfill in Johor Bahru, Malaysia. The most important criterion for this study were residential areas and water bodies while the least important criteria was railway. The study further revealed that, 54% of the study are were unsuitable areas for sanitary landfill site, 12% less suitable, 21% suitable and 13% most suitable. Three most suitable potential sites were identified among the various sites. These three sites have fulfilled the necessary requirements of landfill sites selection guidelines using the geospatial technique.

Government authority, policy and decision makers should integrate the efforts toward a sustainable solid waste management technique taking into consideration the results obtained in this research.

REFERENCES

Ahmad, S. Z., Ahmad, S. M. S.and Wan, H. 2011. Comparative site selection process based on different policies and guidelines for municipal solid waste landfill site. *10th International symposium & exhibition on geoinformation 2011 (ISG 2011), Selangor, Malaysia*.

Chabuk, A., Al-Ansari, N., Hussain, H. M., Knutsson, S.and Pusch, R. 2016. Landfill site selection using geographic information system and analytical hierarchy process: A case study Al-Hillah Qadhaa, Babylon, Iraq. *Waste management & research,* 34**,** 427-37.

Chen, Y., Yu, J.and Khan, S. 2013. The spatial framework for weight sensitivity analysis in AHP-based multi-criteria decision making. *Environmental Modelling & Software,* 48**,** 129-140.

Djokanović, S., Abolmasov, B.and Jevremović, D. 2016. GIS application for landfill site selection: a case study in Pančevo, Serbia. *Bulletin of Engineering Geology and the Environment,* 75**,** 1273-1299.

Ghobadi, M. H., Taheri, M.and Taheri, K. 2017. Municipal solid waste landfill siting by using analytical hierarchy process (AHP) and a proposed karst vulnerability index in Ravansar County, west of Iran. *Environmental Earth Sciences,* 76.

Hengl, T., Gruber, S.and Shrestha, D. 2003. Digital terrain analysis in ILWIS. *International Institute for Geo-Information Science and Earth Observation Enschede, The Netherlands,* 62.

Kemal Korucu, M.and Erdagi, B. 2012. A criticism of applications with multi-criteria decision analysis that are used for the site selection for the disposal of municipal solid wastes. *Waste Management,* 32**,** 2315-23.

Khademalhoseiny, M. S., Nadoushan, M. A.and Radnezhad, H. 2017. Site selection for landfill gas extraction plant by fuzzy analytic hierarchy process and fuzzy analytic network process in the city of Najafabad, Iran. *Energy & Environment,* 28**,** 763-774.

Khodaparast, M., Rajabi, A. M.and Edalat, A. 2018. Municipal solid waste landfill siting by using GIS and analytical hierarchy process (AHP): a case study in Qom city, Iran. *Environmental Earth Sciences,* 77**,** 12.

Madurika, H.and Hemakumara, G. 2015. GIS based analysis for suitability location finding in the residential development areas of greater Matara region. *Int. J. Sci. Technol. Res,* 4**,** 96-105.

Mohamed, M.and Plante, R. Remote sensing and geographic information systems (GIS) for developing countries. Geoscience and Remote Sensing Symposium, 2002. IGARSS'02. 2002 IEEE International, 2002. IEEE, 2285-2287.

Mohammed, H. I., Majid, Z.and Yamusa, Y. B. 2017. Geospatial Based Strategy of Landfill Site Selection for Municipal Solid Waste Management: A Review. *ASIA International Multidisciplinary Conference.* Universiti Teknologi Malaysia.

Mohammed, H. I., Majid, Z.and Yamusa, Y. B. GIS Based Sanitary Landfill Suitability Analysis for Sustainable Solid Waste Disposal. IOP Conference Series: Earth and Environmental Science, 2018a. IOP Publishing.

Mohammed, H. I., Majid, Z.and Yamusa, Y. B. GIS based sanitary landfill suitability analysis for sustainable solid waste disposal. IOP Conference Series: Earth and Environmental Science, 2019a. IOP Publishing, 012056.

Mohammed, H. I., Majid, Z., Yamusa, Y. B., Ariff, M. F. M., Idris, K. M.and Darwin, N. 2019b. Sanitary Landfill Siting Using GIS and AHP. *Engineering, Technology & Applied Science Research,* 9**,** 4100-4104.

Mohammed, H. I., Majid, Z., Yusof, N. B.and Yamusa, Y. B. Analysis of Multi-Criteria Evaluation Method of Landfill Site Selection for Municipal Solid Waste Management. E3S Web of Conferences, 2018b. EDP Sciences, 02010.

Önal, A. Ö., Demirbilek, D.and Demir, V. 2013. Geo-environmental site investigation for Tunceli, Turkey municipal solid waste disposal site. *Engineering Geology,* 159**,** 76-82.

Önüt, S.and Soner, S. 2008. Transshipment site selection using the AHP and TOPSIS approaches under fuzzy environment. *Waste Management,* 28**,** 1552-1559.

Samsudina, M. D. M.and Dona, M. M. 2013. Municipal solid waste management in Malaysia: Current practices, challenges and prospect. *Jurnal Teknologi,* 62(1), 95–101.

Scott, J., Beydoun, D., Amal, R., Low, G.and Cattle, J. 2005. Landfill management, leachate generation, and leach testing of solid wastes in Australia and overseas. *Critical Reviews in Environmental Science and Technology,* 35**,** 239-332.

Wasige, J. E., Groen, T. A., Smaling, E.and Jetten, V. 2013. Monitoring basin-scale land cover changes in Kagera Basin of Lake Victoria using ancillary data and remote sensing. *International Journal of Applied Earth Observation and Geoinformation,* 21**,** 32-42.

Yesilnacar, M. I.and Cetin, H. 2008. An environmental geomorphologic approach to site selection for hazardous wastes. *Environmental Geology,* 55**,** 1659-1671.