APPLICATION OF GIS IN LANDFILL SITE SELECTION FOR SOLID WASTE MANAGEMENT IN AN URBAN ENVIRONMENT

Tafadzwa MANDIZVIDZA

Midlands State University, Gweru, Zimbabwe

Dr. Chipo MUTONGI

Zimbabwe Open University, Harare, Zimbabwe

Dr. Smartson. P. NYONI

ZICHIRe Project, Harare, Zimbabwe

Thabani NYONI

University of Zimbabwe, Harare, Zimbabwe

Abstract:

Less economically developed countries are facing challenges resulting from poor solid waste management due to a number of reasons such as the rise in urban population, the construction era, industrial growth, and unsustainable consumption practices. Site selection of waste disposal and waste management for developing countries always pose major challenges. The application of Geographical Information Systems (GIS) and Multi-Criteria Decision Analysis (MCDA) in the location of landfills is still in its infancy. In this study we tested the suitability of pre-existing landfill locations by comparing them with the newly located landfills in the study area. In order to locate the sites of appropriate landfills, applied the Analytic Hierarchy Process (AHP) model of MCDA during criteria evaluation to give each criterion weight matching its importance. Our findings show that most suitable landfill sites constitute a low percentage (0.11%) than unsuitable area (91.95%). The Jaccard test produced an overlap of 22.72% and high deviation between the newly located landfills and the pre-existing Pomona landfill. Comparisons of the extent of suitable area for landfill site selection show that the proportions differ significantly ($\chi 2 = 7305.8$, df=2, $p<0.0001$). Our study is a cost effective verifiable tool in landfill site selection and assessing suitability of landfills to make economic and environmentally conscious decisions so as to ensure minimum damage to the environment.

Keywords: *Geographical Information System (GIS), Multi-Criteria Decision Analysis (MCDA), Waste Management, Landfill Siting*

INTRODUCTION

Current waste management practices have failed to cope with the rapid generation rates. Global municipal solid waste generation is expected to rise from approximately 1.3 billion tonnes per year to 2.2 billion tonnes per year by 2025 (Hoornweg & Bhada-Tata, 2012). In most developing countries, 65 to 85% of waste generated is collected and disposed while the rest is uncollected. Southern Africa regional statistics have found that waste generation is 62 million tonnes per year at an average rate of 0.65 kg/capita/day. The landfill method is a widely used approach for disposal of solid waste across many countries. In most cases these landfills have become unsustainable and have exceeded their carrying capacity of municipal solid waste. Decisions on optimal landfill selection are a challenge is developing countries. A study by (Masocha & Tevera, 2004) found high soil lead (Pb) contamination down-slope of the Victoria Falls Municipal dumpsite. The siting of landfills has also proved challenging for cities such as Harare. For example, the Pomona landfill is not properly engineered and has a number of challenges such as fires and vermin affecting locals.

This study will test the application of GIS and MCDA in the location of suitable landfills. In order to meet the objective, several criteria shall be evaluated using methods such as Multi-Criteria Evaluation (MCE). Several relevant studies on landfill siting have been carried out in developed countries (Alanbari, Al-Ansari, & Jasim, 2014; Khan & Samadder, 2015; Şener, Sener, & Karagüzel, 2011). However, the application of GIS and MCDA in location of landfills is still in its infancy. A study by (Pawandiwa, 2013) integrated GIS and MCDA in Southern Africa but no studies have validated the sustainability and location criteria used of the pre-existing landfills. This research will integrate GIS and MCDA to locate suitable sites using optimal stipulated criteria. The study will also compare the sustainability of the pre-existing landfills against that of newly located landfills.

Study Area

Harare province is located northwest of Zimbabwe (fig. 1). It lies between latitude 17°43'S and longitude 31°02'E and has an area of approximately 94097.40ha. The average yearly rainfall varies between 830mm to 860mm. The average annual temperature is 8°C -23°C in winter, 15°C - 31°C in summer. The geology is 37% sedimentary, prone to erosion and is also prone to aquifer pollution. The ground water table ranges from 5m to 25m. As per census of 2012, Harare had a population of 2123132 which is 12.7% of the total population with an average growth rate of 2% (Zimstat, 2015).

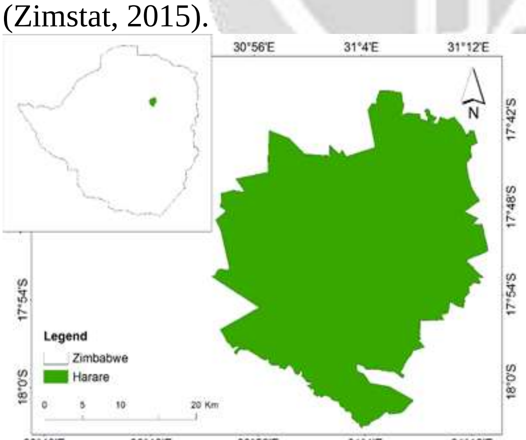


Fig. 1: The study area: Harare, Zimbabwe

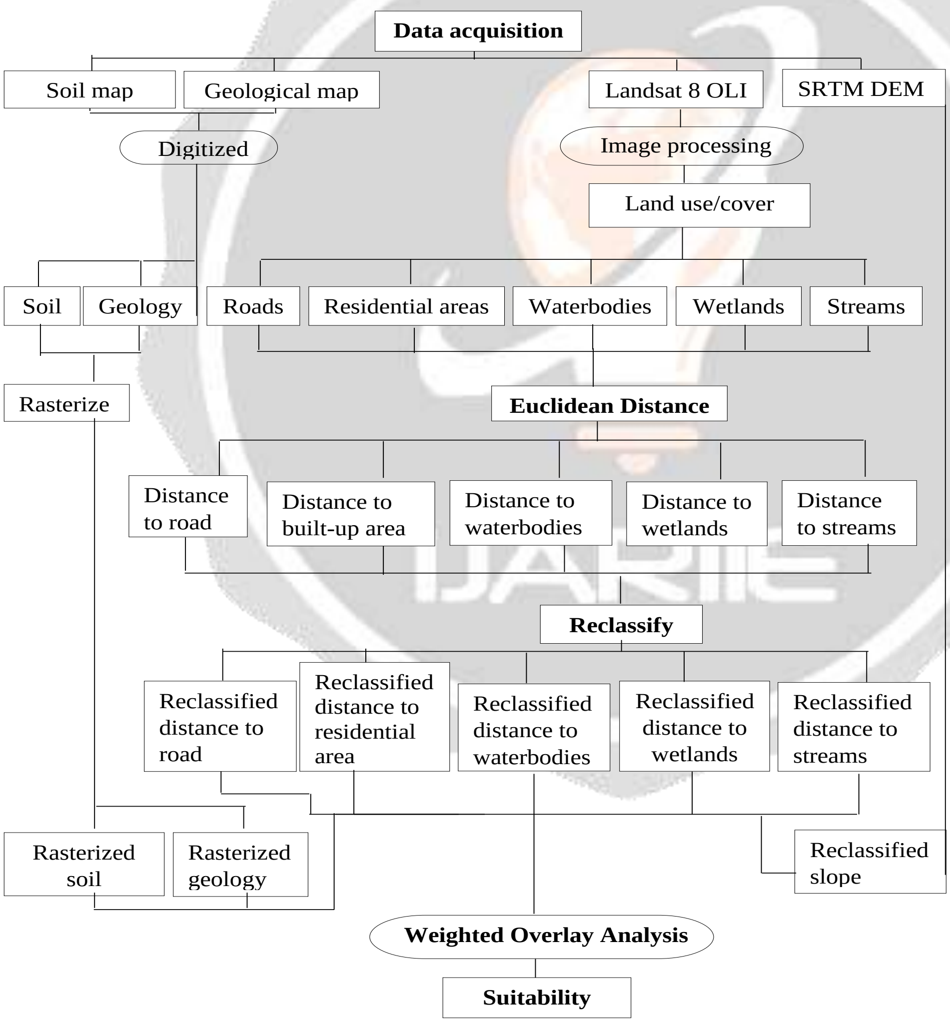
METHOD

Testing for Landfill Suitability

This was done based on previous studies (Alanbari et al., 2014; Khan et al., 2015; Pawandiwa, 2013). Satellite images were obtained from (http://earthexplorer.usgs.gov). To achieve imaging and spatial analysis, we projected the data from different coordinate systems to WGS UTM Zone 36S. We used GIS and Remote Sensing to radiometrically correct image pixels and classified the enhanced Landsat-8 Operational Land Imager (OLI) image using supervised classification to create classes representing phenomena in space. We extracted built-up area using Normalized Built-up Difference index (NDBI) (Bhatti & Tripathi, 2014), wetlands using Normalized Difference Vegetation Index (NDVI) (Xu, 2007) and water bodies. We obtained a Shuttle Radar Topography Model Digital Elevation Model (SRTM DEM) of the study area, then extracted slope and streams. The method used in this study is shown in the conceptual model in (Fig. 2) and explained in detail in the following sections:

Fig. 2: Flow chart of Landfill site Selection

Factors considered



We identified built-up area as a restrictive factor when siting a landfill. Areas close to residential developments, and other sensitive institutions such as hospitals are not suitable for waste disposal to avoid endangering public health due to pollutants (Pawandiwa, 2013). We also identified roads to be important because a considerable distance from the road to reduces visual nuisance. We identified wetlands, water bodies, streams so as to avoid contamination of ground and surface water (Fig. 3). We identified slope as important since landfill disposal is appropriate on flat land as opposed to rugged, broken terrain (Josimović & Marić, 2012). We also identified soil type as (EPA, 2015) recommends sites with clayey, than sandy soils. Lastly, we considered geology in the suitability analysis to determine locations that require less engineering assistance.

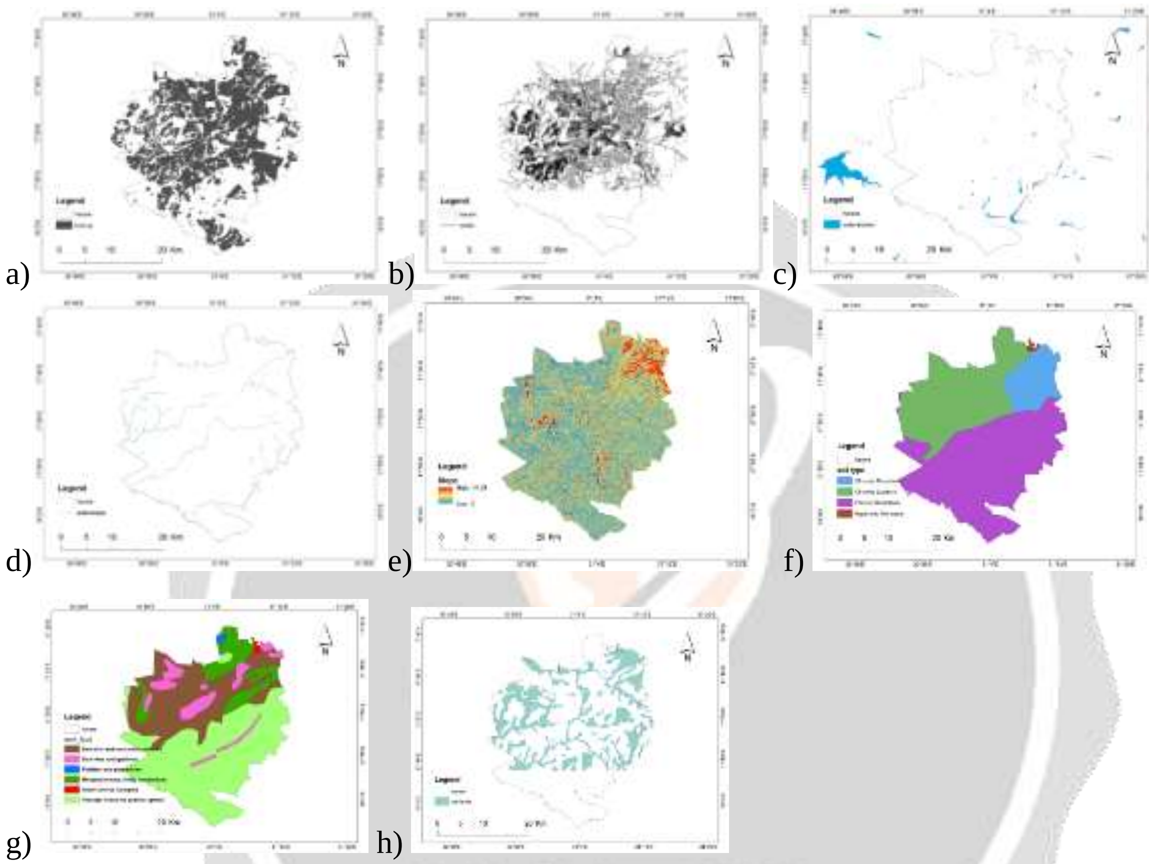


Fig. 3: Physical criteria considered for the study area: (a) built-up (b) roads (c) waterbodies (d) streams (e) slope map (f) soil map (g) geology (h) wetlands

Site Area Requirement

We also calculated the minimum site area requirement for a landfill to meet standards based on (Alanbari et al., 2014). To meet current and future minimum requirements of the landfill, it was necessary to project the site area requirement for Harare for the next 20 years based on (Nascimento & da Silva, 2014), on the formula:

$$N = (No\ (1 + Tx/100)\ ) * t \qquad \textit{(equation 1)}$$

Where: *N* is population, *No* is initial population, *Tx* is percentage of annual increase and *t* is time in years.

Criteria Weights

We used AHP technique based on Saaty (1977) to evaluate each criterion. The pairwise comparison allows to calculate weights by comparing two criteria at once in a spreadsheet environment that can be input into GIS based decision making.

Test for consistency

We did the test for consistency for the comparisons based on (Alanbari et al., 2014). Consistency index is an average value of consistency. Consistency ratio measures departure from consistency.

a. Consistency index (CI) = ($\lambda max - n$) / (n −1) *(equation 2)*

b. Consistency ratio (CR) = CI/ RI *(equation 3)*

: Where RI is the random index (depends on number of criteria); CR < 0.1, represents consistency and CR≥ 0.1, represents inconsistent judgments.

Euclidean Distance

We established buffer zones to each criterion map layer to obtain safe distances at which an optimum landfill can be located. Buffer areas may not be a way of promoting sustainable management practices, but reduce contingencies resulting from varying management practices (EPA, 2015). The first buffer has the least weight as it is close to criteria.

Reclassification

We reclassified the buffer distance map layers of criteria to be able to standardize them for ranking and overlay. Reclassification of criteria ranges from 0 (not suitable) to 9 (most suitable) according to (Nwosu & Tamunobiekiri, 2016).

Weighted Overlay

Weighted overlay is a method in which raster layers are overlaid and multiplied by their particular weights then adding them. The standardized criteria and their weights from the comparison matrix were incorporated into the MCE (Minalu, 2016) to obtain the suitable landfill sites. The formula used was based on (Khan et al., 2015) is:

$$S = \sum_{i=1}^{n} w_i * x_j \prod_{j=1}^{m} c_j \qquad (equation\ 4)$$

Where: S = Composite suitability score, xi = Criterion score, wi = Weight of each criterion,

cj = Constrains, Σ= Sum of Weights and Π= Products of constraints.

The Jaccard Index

We used the Jaccard's test (Jaccard, 1912), to quantify the area overlap between the pre-existing landfills and the newly located landfills. It ranges between 0% and 100%, a lower percentage shows low similarity and a higher percentage shows more similarity between two populations. It is calculated as follows:

J (X, Y) = (A∩ (X, Y)) / (A∪ (X, Y)) *(equation 5)*

Where: X and Y - spatial objects that have area; A∩ - overlapping area of polygons; and A∪ - union area of polygons.

The Chi Square test

We did a test of proportions in R Studio between the least suitable, moderately suitable and most suitable landfill site locations using the respective extents of area. This was to test whether there is a significant difference between these sites.

RESULTS

The current minimum site area requirement based on the projected 2017 population of 2 344 019 is 166.03ha. The projected volume of waste generated in year 2032 is 364 763.6m³, density, 0.32 t/m³ and mass, 238407.6t. The projected site area requirement is 248.77ha for 2032 for a population of 3 173 129 and a minimum life span of 20 years.

Table 1: Distribution of suitability in the study region.

Rank	Suitability	Area(ha)	Percentage (%)
6	Most suitable	101.85	0.11
5	Moderately suitable	2233.70	2.37
4	Least suitable	3848.97	4.09
3	Least suitable	1107.20	1.18
2	Unsuitable	287.53	0.31
0	Unsuitable	86518.15	91.95
Total		94097.40	100

Our findings show that more suitable landfill locations are mostly in the southern Eastern part of Harare (fig. 5). 3 sites of suitability class 6 are located on the southern part and 1 site is located on the northern part of the study area. In suitability class 5, 30 sites are located in the south eastern part and 18 sites are in proximity to the western boundary of the study area. In suitability class 2 and 3, the landfill locations are sparsely distributed are mostly at the eastern boundary and a few close to the western boundary (fig. 5).

We also found that Harare rural district has more moderately suitable sites and has one landfill site location in class 6 (fig. 4b). 67% of Harare rural district is occupied by more suitable sites. Chitungwiza district has 2 most suitable sites and 14% of this district is suitable for landfill site location. Class 5 is the highest level of suitability in Harare urban district while 4% of the district is suitable. 96% of Harare urban district is unsuitable and the suitable sites are located on the eastern boundary of the district. However, 89% of northern Harare is suitable. The northern part also contains 9 sites in suitability class 5 and 1 site in suitability class 6. Epworth district and Seke have no suitable landfill locations.

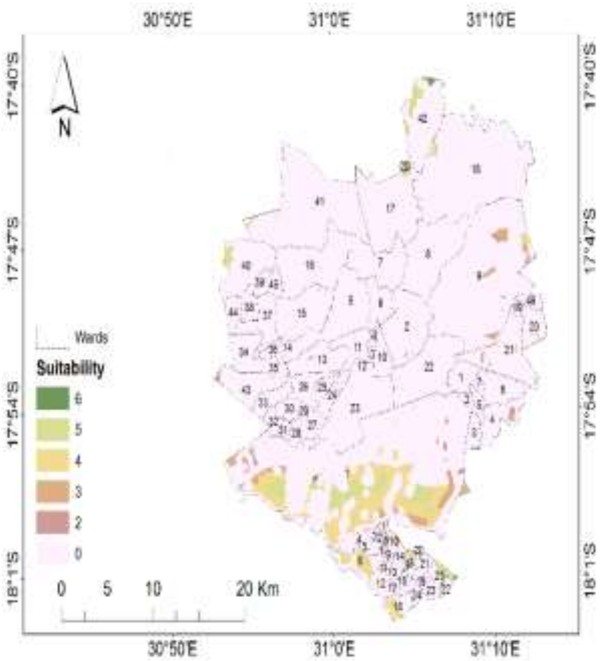
Our findings show that ward 1 has more suitable landfill locations (fig. 4a). 67% of ward 1 is occupied by suitable landfill sites. Wards 9, 20, 21 and 46 on the eastern boundary of the study area have least suitable sites. Wards 3, 4, 5 and 8 are not suitable for landfill site location (fig. 4a). We found that 20.8% area of the pre-existing Pomona landfill coincides with a moderately suitable location in ward 20. 26.6% area of the new moderately suitable landfill coincides with the pre-existing Pomona landfill (fig. 5).

Most suitable locations constitute a low percentage than moderately suitable area (table 1). Our findings also show that suitability class 6 of most suitable locations constitutes a lower percentage of the study area and class 0 which is unsuitable constitutes a higher percentage of the study area (table 1). In terms of area, the sites of suitability class 4 indicated most suitable area for landfill siting (table 1).

The criteria analysis resulted in built-up area having the larger weight. The test for consistency shows λmax = 12.11, CI = 0.11, RI = 1.41 and CR = 0.08< 0.1. The consistency ratio shows significant pairwise comparisons.

The Jaccard test produced an overlap of 22.72% between the newly located landfills and the pre-existing Pomona landfill. Overlapping area is 35.48ha. Union area is 156.49ha.

Comparisons of the extent of suitable area for landfill site selection show that the proportions differ significantly ($\chi2 = 7305.8$, df=2, $p<0.0001$).



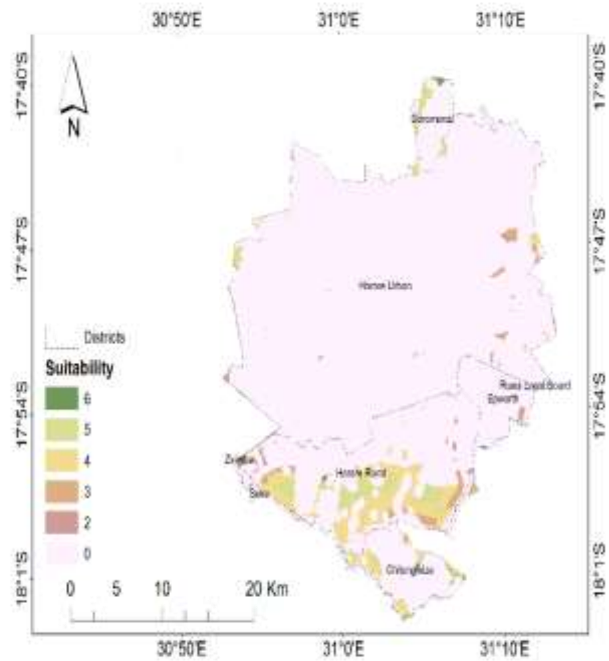


Fig 4a: Suitability in wards. Fig 4b: Suitability in districts.

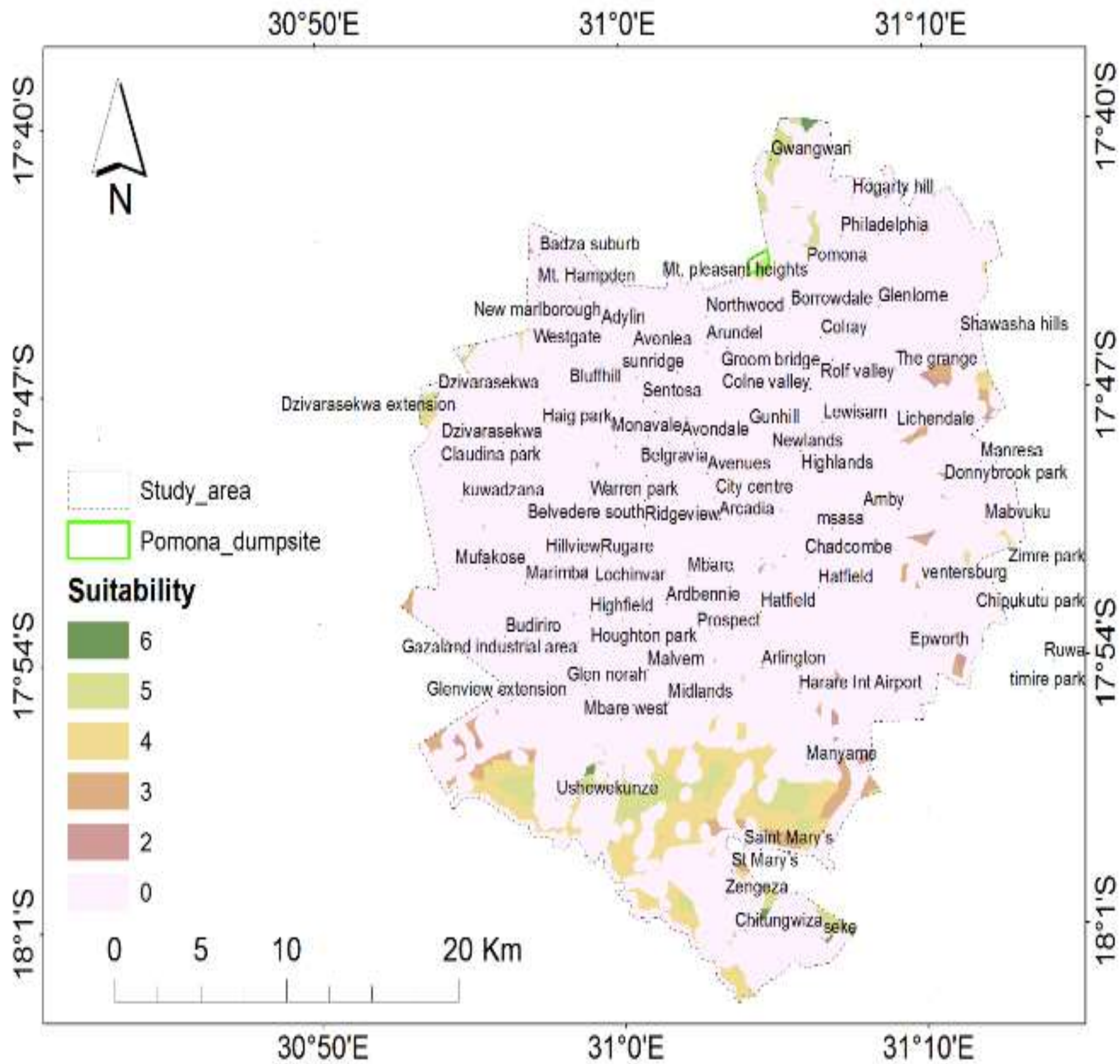


Fig. 5: Final landfill suitability map

DISCUSSION

The hypothesis of this study was that there is no difference between the pre-existing landfill locations and the newly located landfills.

Using the Jaccard index, we found that there is high deviation between the newly located landfill sites and the pre-existing landfill sites. In this study we observed that a small proportion of the Pomona dumpsite coincides with a small proportion of a moderately suitable site. The other proportion of the dumpsite is not suitable for a landfill site thus making the dumpsite unsuitable for disposing waste. This may be because the City council did not use any landfill locating criteria but instead select abandoned quarries as landfills. (Mangizvo, 2008) also found that the City council did not use any stipulated landfill site selection criteria in Masvingo. We validated our approximations using the proportions test in which there is no similarity between the moderately suitable sites and the most suitable sites. The 3-sample test for equality of proportions shows there is a significant difference between the least suitable, moderately suitable and most suitable sites in terms of their area.

In this study we were able to use scientific methods to determine appropriate location of optimal landfill sites. Our key findings showed that 86% of the suitable sites were observed to occur in open areas which are barren (with low economic land use). The suitable sites are densely located in the south eastern part of Harare occupied by the Harare rural district in Ushewekunze district. This is because the south eastern part of Harare is largely occupied by open areas and has low settlement as compared to other areas such as Chitungwiza and Epworth. The areas with more suitable site locations have low population which means low waste generation rates. Additionally, Harare urban is not suitable for a landfill site as it is clustered with high economic land use activities and environmental value such as settlements and wetlands respectively. We also observed that most suitable sites are located on the margins of the study area. However, (Pawandiwa, 2013) made a similar observation where suitable sites were located in proximity to the boundaries of the study area. The boundaries are the outskirts of an area where mostly the criteria evaluated in this study are low and sparsely distributed such as roads and built up.

The pairwise comparisons among the criteria were consistent as they scored a consistency ratio less than one. This shows that the judgements made during the weighting were in line with the landfill suitability analysis being done. The consistency ratio also showed that the criteria used int this study were appropriate for the landfill suitability analysis. The level of consistency our pairwise comparisons scored increased the accuracy of weightages of criteria used in this study.

In our study we also observed that by the year 2032, the minimum site area requirement will increase due to the increase in waste generation rates. The projected minimum site rea requirement was larger than the pre-existing landfill area. This reduces the life span of the landfill. In our study we made a similar observation to that of (Makwara & Snodia, 2013), that dumpsites currently being used in Harare do not meet population dynamics and waste generation rates.

However, our study did not include all the criteria necessary to locate an optimum landfill thus there is need to use other variables to improve accuracy in determining the most suitable landfill sites. Although our study follows pre-established criteria, buffer distances were considered according to local conditions to avoid overlapping into certain land use but this may affect the suitability analysis as judgements must also be based on several factors such as social and economic criteria.

CONCLUSION AND RECOMMENDATIONS

This study was a verifiable tool in showing that the pre-existing dumpsites highly deviate from the optimal stipulated criteria. The choosing of landfill sites by most municipalities is done in a haphazard manner which is unscientific. The suitability analysis carried out in this study is cost effective in identifying suitable locations for a landfill. The suitability of these sites significantly varied due to their various proximities to different criteria. The criteria used was consistent and suitable sites were found to exist in open areas which did not coincide with other important economic land uses. It is key to mention that most areas in which suitable sites are located, there are low populations thus low waste generation rates. This is opposed to Harare urban where no suitable was found due to clustering of built-up thus a high population base and high waste generation rates. The local authority urgently needs to locate a new area for a landfill as the pre-existing landfill has overlapped its life span and is unsustainable for dumping waste.

REFERENCES

Alanbari, M. A., Al-Ansari, N., & Jasim, H. K. (2014). GIS and multicriteria decision analysis for landfill site selection in Al-Hashimyah Qadaa. *Natural Science, 2014*.

Bhatti, S. S., Tripathi, N. K. (2014). Built-up area extraction using Landsat 8 OLI imagery. *51*(4), 445-467.

EPA. (2015). Siting, design, operation and rehabilitation of landfills.

Hoornweg, D., & Bhada-Tata, P. (2012). *What a waste: a global review of solid waste management* (Vol. 15).

Jaccard, P. (1912). "The distribution of flora in the alpine zone". In: The New

Phytologist, vol. 11(2), p. 37-50.

Josimović, B., & Marić, I. (2012). Methodology for the Regional Landfill Site Selection. *Sustainable Development–Authoritative and Leading Edge Content for Environmental Management*, 513-538.

Khan, D., Samadder, S. R. (2015). A simplified multi-criteria evaluation model for landfill site ranking and selection based on AHP and GIS. *23*(4), 267-278.

Makwara, E. C., & Snodia, S. (2013). Confronting the reckless gambling with people's health and lives: Urban solid waste management in Zimbabwe. *2*(1), 67-98.

Mangizvo, R. V. (2008). Management practices at the Mucheke municipal solid waste disposal site in Masvingo City, in Zimbabwe. *10*(2), 147-164.

Masocha, M., & Tevera, D. (2004). Variations in lead (Pb) content in soils downslope and upslope of Victoria Falls municipal waste dump, Zimbabwe. (35-36), 27-33.

Minalu, A. (2016). *Solid Waste Disposal Site Selection Using Gis And Remote Sensing: For Mojo Town, Ethiopia.* AAU,

Nascimento, V. F., & da Silva, A. M. (2014). Identifying problems for choosing suitable areas for installation of a new landfill through GIS technology: A case study. *Journal of the Air & Waste Management Association, 64*(1), 80-88.

Nwosu, E. E., & Tamunobiekiri, G. (2016). Site Selection and Analysis of Solid Waste Dumpsites in Ile-Ife, Nigeria.

Pawandiwa, C. C. (2013). Municipal solid waste disposal site selection the case of harare.

Şener, Ş., Sener, E., Karagüzel, R. (2011). Solid waste disposal site selection with GIS and AHP methodology: a case study in Senirkent–Uluborlu (Isparta) Basin, Turkey. *173*(1-4), 533-554.

Xu, H. (2007) Photogrammetric Engineering Remote Sensing.. Extraction of urban built-up land features from Landsat imagery using a thematicoriented index combination technique. *73*(12), 1381-1391.

Zimstat. (2015). Population Projections Thematic Report August 2015.