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Landfill Site Suitability Analysis Using Geographic Information System and Remote Sensing for Thohoyandou Town, South Africa

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ABSTRACT

Disposal of solid waste is a major challenge in towns and cities due to waste being dumped at an unacceptable site. The designation of a landfill site is a challenge in Thohoyandou town. The purpose of this study was to determine a user-friendly landfill site location for Thohoyandou town. The study also intended to examine the social implications of the existing landfill site location on the communities. Data was gathered using both qualitative and quantitative methods. Data was acquired using questionnaire surveys, interviews, field survey, observations, and secondary sources. The data was analyzed using the Statistical Package for Social Scientists, and the Chi-square test. Geographical Information Systems (GIS) and Remote Sensing (RS) constitute the major methods used to determine an acceptable site for the disposal of solid waste generated in study area. The existing landfill site in the study area is not in line with environmental and social standards due to waste being dumped at an unacceptable site. The study revealed social problems such as bad smell, diseases, noise, dust and decline of standards of living in which all have emerged because of the Thohoyandou Block J landfill site. To overcome these challenges, this study incorporated six environmental parameters, including: proximity to road networks, slope, soil, land use/land cover, and built-up areas; surface water, to determine the best suitable landfill site in the study area. According to the findings of this study, out of five potential landfill sites, the site which had the highest rankings following the Analytical Hierarchy Process (AHP) was selected as the most suitable landfill site. As a result, the research recommends that Thulamela Local Municipality contemplate terminating its existing landfill site to relocate to one of the alternative acceptable sites identified by this study.

1. INTRODUCTION

Throughout the world, the managing of municipal solid waste is among the most environmental challenges that most towns and cities face because of increasing population concentration that generate a significant amount of solid waste. Both developed and developing countries uses a variety of waste management strategies, such as recycling, landfilling, and incineration. There are many different forms of waste that are produced, including electronic, metal, plastic, and solid waste. However, only a small percentage of these wastes are disposed of in landfills, as shown by Germany's import of tons of waste for recycling. Landfills are sited according to a set of standards, to minimise their impacts on the environmental [1].

Municipalities in developing countries, on the other hand, have found it challenging to handle their solid waste because of financial constraints. In Africa, one of the challenges with landfill siting is that some municipal solid wastes are disposed of in unsuitable locations, causing further harm to humans. As state in the article [2], despite various studies pushing for the use of Geographical Information System (GIS) technique in landfill siting in several Zimbabwean municipalities, GIS is not yet frequently employed in landfill siting. People in the waste management field, like those in other industries, are mostly unaware of the significant usefulness of GIS and Remote Sensing (RS) application in managing waste. Waste management has become a major problem in environmental planning due to a lack of understanding about new and emerging technologies for environmentally friendly and effective performance. GIS is the most acceptable and resilient method for sitting landfills since it can identify the selection guidelines to be utilized for landfill site.

There are still a lot of studies done in South Africa which show that landfills are being sited in a crude fashion even in the technological society. In South Africa especially the study area of Thohoyandou town, landfill is the main common solid waste disposal method. Solid waste is dumped of at the Thohoyandou Block J landfill (TBJ) site, which is not considered suitable for the dumping of waste as it does not comply with international and national standards [3]. The crude method to determining landfill siting does not take environmental, social, political and economic factors into account [4]. This is due to a lack of knowledge about Geographic Information Systems and Remote Sensing methods, which incorporate all these factors into account.

The expansion of Thohoyandou has resulted in the dumping site being in built-up areas, posing high risk of disease transmission, fire dangers, odor, air pollution and economic losses [5]. The smoke from the TBJ landfill site slowly spreads over the TBJ, Maniini, Tswinga and Shayandima housing areas at night and on still days, posing a health risk to the inhabitants. Runoff water from the landfill site also poses health risk to residence.

Therefore, this research seeks to perform a suitability analysis using GIS and RS methods to select the most appropriate landfill site. The use of GIS and RS to select a landfill site is a significant step towards improving environmental sustainability in all areas. Thulamela Local Municipality (TML) will use the results of this study to determine which landfill will have the least harmful impact on the environment and community. The study's criteria can also serve as a guide for town planners when evaluating landfill suitability, helping them to determine which landfills are best for social, economic and environmental reasons. This study is a necessity as it will analyse the environmental and ecological consequences of the existing landfill site and provide methods to mitigate these consequences.

There has never been any research done in the town on using GIS and RS technologies to determine a suitable landfill site. It is against this background that this study pursues to find a suitable site for landfills and handling it to overcome the current problems of managing waste in the local municipality.

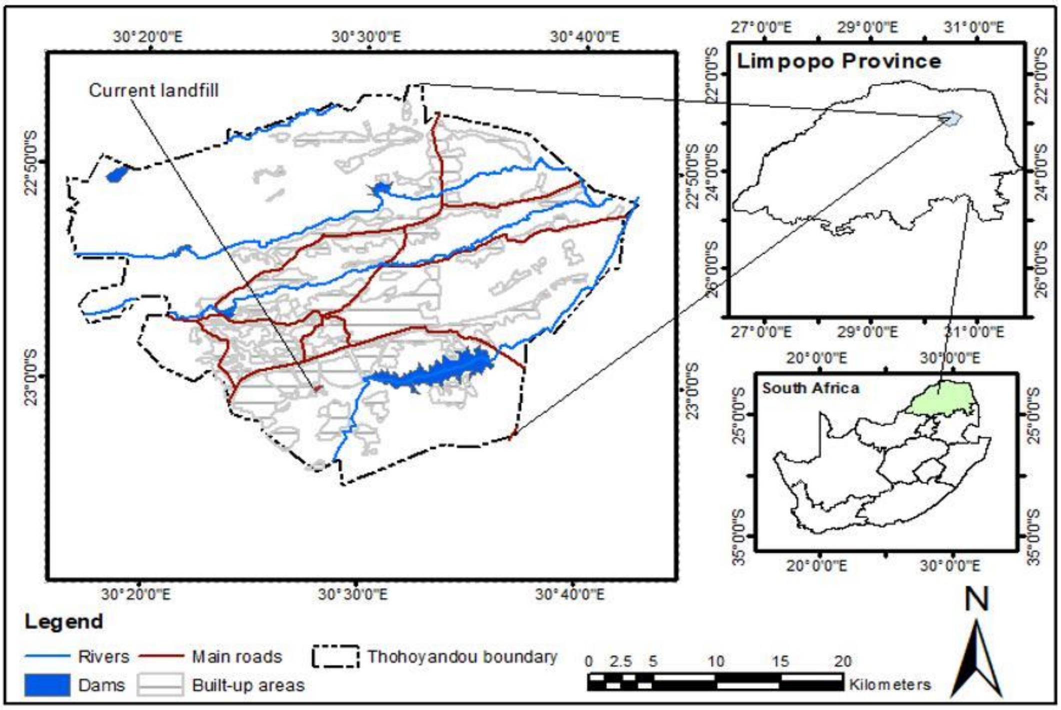

Figure 1. Study area map: Thohoyandou town
Source: Author

2. MATERIAL AND METHODS

2.1 Description of the study area

The study area (Thohoyandou town) of the Thulamela Local Municipality is located mainly in the Limpopo Province (Figure 1). Thulamela Local Municipality is situated on dry grassland at longitudes 23°00′13.0″S and latitude 30°27′55.3″E, at an altitude of 1,395 meters above sea level. Thohoyandou receives approximately 752 mm of rain every year, with most rainfall occurring during midsummer.

Geologically, Thulamela Local Municipality is underlain by Precambrian basalts of the Sibasa Formation of the Suspenser Group to the north and leucocratic biotite gneiss, leucocratic granite and pegmatite, grey biotite gneiss and migmatite of the Sand River Gneiss of the Central Zone of the Limpopo Belt to the south. Moreover, a wide spectrum of loam and sandy occurs in the study area of the present research with clay soils being least common DIWA (2012).

2.2 Methods

This research used both quantitative and qualitative methods. A map of suitable landfill sites was then created using GIS and RS techniques. The quantitative methods of Boolean logic calculations, tables, map algebra and graphs were accompanied with qualitative approach.

Both primary and secondary data were used in this study. Primary data were obtained through field surveys, open-ended questionnaires, interviews and observation. Secondary data were obtained from the books, internet, governmental agencies, journals and other documents. Considering the international origin of landfill-siting concept using GIS and RS, data from secondary sources (Table 1) was of paramount importance.

Table 1. Acquired data sets and their sources

Shapefile	Source
Thohoyandou built up area	Google Earth 2021
Thohoyandou rivers	DIVA-GIS and Mapcruzin
Digital elevation model	U.S. Geological Survey 2021
Thohoyandou roads	Mapcruzin and DIVA-GIS
Thohoyandou town boundary	DIVA-GIS
Soils	FAO
Land use/Land cover (Landsat 8)	U.S. Geological Survey 2021

To identify the significance difference between social impacts and wellbeing of people in the study area, an independent sample chi-square-test was conducted. Numeric data from questionnaires and interviews were analyzed using Statistical Package for Social Sciences version 16.0.

The residents in TBJ, TLM employees and Department of Environmental affairs (Limpopo province) representative in Thohoyandou defines the target population of this study. TBJ houses were picked at random. A total of 10% of the 1428 households in TBJ were chosen to share their opinions on the current landfill site's social impacts. Organizations were selected using the purposive sampling methods, with respondents selected for their specific and implicit ties to the issue.

Individuals having intimate knowledge of the Thohoyandou landfill site were interviewed face to face. This includes members of the TLM, the Department of Environmental Affairs (Limpopo Province), and residents of TBJ. The social and ecological effects that the existing landfill site is having on the community and the environment were better understood through interviews. A semi-structured interview guide was used to interview the selected individuals. In addition to the semi-structured questions, respondents were questioned about their opinions on the issues discussed throughout the interview.

2.3 Restriction of locations using buffer zone

Choosing the best landfill site requires a detailed analysis. Each site must meet national standards while minimizing the environmental, social and economic costs [6]. Using the special extension tool "buffer," buffer zones were created around significant environmental parameters in the GIS. The buffer zones for rivers (1000m), road network (1000m), slope (<120), built-up area (1000m), and soil (clay) were created [7].

2.4 Suitability analysis methods

2.4.1 Multi-criteria evaluation

The detailed database for this research included built-up areas, highways roads, slopes, rivers, soils and land use/land cover, which were all organized in ArcMap 10.5. ArcMap 10.5 convection tools were then used to convert these parameters from vector data to raster data. The prerequisites for the landfill were assessed in two stages, with the first defining unacceptable waste dumping packages. Based on the results of the disposal method, the defined qualified land packages were evaluated using the analytical hierarchy technique.

Individual raster layer was assigned to nine classes, prior to reclassification and remodelling layers were also assigned the same way. The Euclidean distance under spatial tool in ArcMap was used to classify distance-related parameters such as rivers, roads, built-up areas and nature reserves. However, other parameters such as slope, lithology and soil were classified under spatial tool in ArcMap.

The criteria of Buffer Zone were used to reclassify previously classified raster layers. Reclassification was performed to create two different zones on each raster map showing acceptable and unacceptable sites. Reclassification was performed using spatial analyst tools, binary values "0" and "1" were allocated to the two classes, indicating unsuitable and suitable sites respectively.

The Boolean logic "And" was used to merge the reclassified raster maps indicating suitable and unsuitable sites. These calculations led to the combining of all reclassified raster maps and unsuitable ("0") sites were multiplied by zero to create a class of zeros across all raster maps. All reclassified areas of "1" were multiplied by one to produce a suitable site of one. By using this Multi-criteria evaluation process, a map of potential landfill sites was created.

2.4.2 Analytical Hierarchy Process (weighted overlay analysis)

This study assessed the final suitability index using an Analytical Hierarchy Process (AHP) method instead of the other four methods available because it is the most acceptable technique for solving such a comprehensive and multi-faceted problem. Ndeke [8] developed AHP as a scientific way of calculating ration scales based on paired comparisons and used to help top management in coming-up with the best decision in the case of case of complex conflicting criteria. A pair-wise comparison approach was used to calculate the relative significant weights for each criterion based on judgment and expertise of the area. A pair-wise comparison examines two items' relative value, desirability or probability regarding another item. The decision-making process was enhanced because of this pair-wise comparison [9]. Depicts nine-point rating system ranging from 1 (equal importance) to 9 (extreme importance), which was utilised as a guide in the pairwise comparison.

The paired comparison matrix was created using the pairwise comparison scale. Individual factor in question was represented by one row and one column. As a result, the AHP was split into comprehensible decision issues based on variables; individual of these components was investigated individually and logically combined [10].

A pairwise comparison matrix website was utilized to calculate the weights. Since there were no substitutes, variables such as towns, rivers and slope were assigned the greatest scores. Roads were assigned the least value in the online pairwise comparison matrix.

Following the calculation of the individual criterion weights, individual reclassified raster map was assigned a weight based on the results from the pairwise comparison matrix. By using weighted overlay analysis, a map showing areas which are most suitable to most unsuitable was created. Maps of the weighted overlay analysis and prospective landfill sites were combined. A final suitability map was created by merging areas indicated as suitable, by weighted overlay analysis with areas defined as suitable through Multi-criteria evaluation.

3. RESULTS AND DISCUSSIONS

3.1 Determine selection criteria to be used for locating a landfill site

3.1.1 Suitability against surface water

Al-Yaqout et al. [11] indicate that if a landfill is too close to rivers and dams, toxins from the landfill are likely to leak into the groundwater and flow into rivers and dams. Njoku et al. [12] indicate that the suitability of a landfill site was limited by 900 meters from surface waters; any area below this point was regarded a restriction and rejected. Similarly, a minimum distance buffer zone of 1000m was accepted in this study. This is because areas within this buffer zone are unsuitable since their subsurface water level is high, discharge is high and downstream effect is strong. Thus, Figure 2 shows that after applying the Boolean logic operation "And", 80% of the areas are found to be suitable, whereas 20% are not.

3.1.2 Suitability against major roads

The landfill should be situated near a road to reduce transportation costs. Thoso [13] employed a minimum distance of about 750m away from main roads to minimize costs associated with transportation. Those areas located within a buffer distance of 750m were classified as unsuitable. On the other hand, Şener et al. [14] created a waste site 800m away from major roadways due to environmental problems and a foul odor impacting the surrounding area. Based on similar environmental problems, this buffer distance was accepted in this study. A distance of 1000m away from the main roads is the most appropriate for disposal sites in Thohoyandou. Therefore, considering these criteria, 15.5% of the study area was unsuitable while 75.5% was suitable as shown in Figure 3.

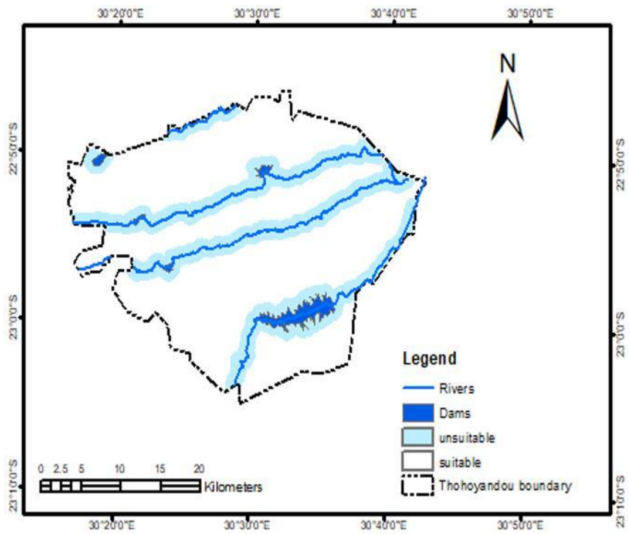

Figure 2. Main rivers and dams of Thohoyandou

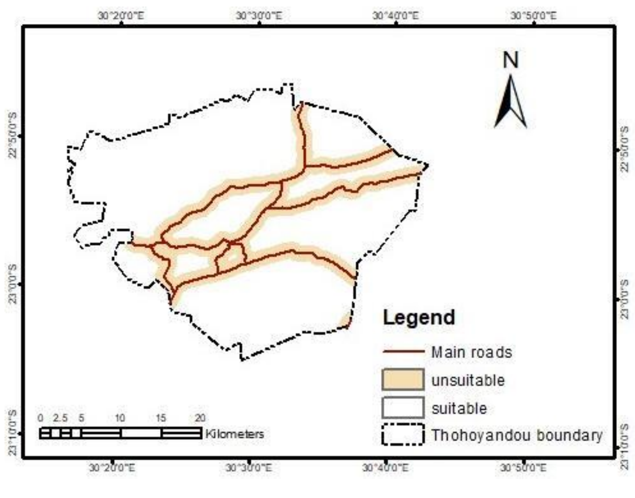

Figure 3. Major roads in Thohoyandou study area

3.1.3 Suitability against slope

For landfill construction, an average steepness of roughly 8-12 degrees is ideal [15]. This is because a slope which is too steep would be hard to build and maintain, while a slope that is too gentle would interfere with runoff drainage. Slope steepness of below 3 degrees was accepted by Sharifi et al. [16] as the most suitable for landfill sitting. Similarly, this study accepted a slope of below 12 degrees because most of the study area had an average slope of less than 12 degrees. Figure 4 illustrates that a slope of more than 12 degrees was found on the northwest side of Thohoyandou town and was deemed unsuitable. According to the above criterion, areas that were found to be unsuitable constitutes 40%, whereas 60% is suitable.

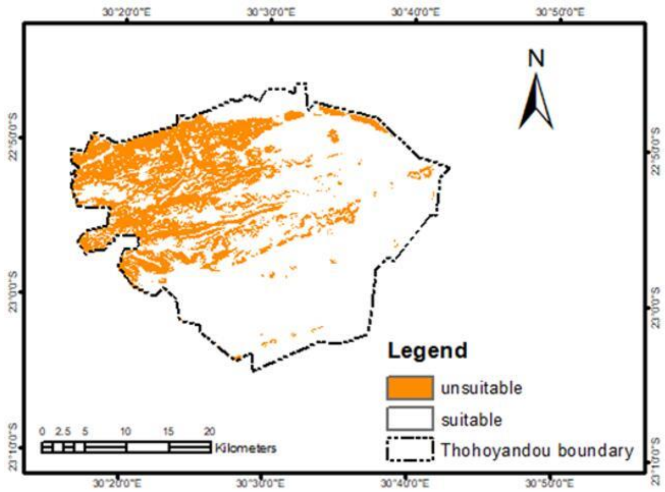

Figure 4. Slope of Thohoyandou study area

3.1.4 Suitability against built up areas

González-Torre and Adenso-Díaz [17] stipulate that a disposal site should not be situated too near to built-up areas in order to protect the health and well-being of those who live close. Guerrero et al. [18] employed a buffer distance of 1100m away from built-up areas. Chang et al. [19] advised that a landfill site within a 700m buffer zone should be avoided since landfills are associated with poor odours, noise and health hazards. A 700m distance from built-up areas was set in this study due to comparable environmental issues and health risks. According to the above criteria, Figure 5 demonstrate that unsuitable areas account for 70% of the total, while suitable areas account for 30%.

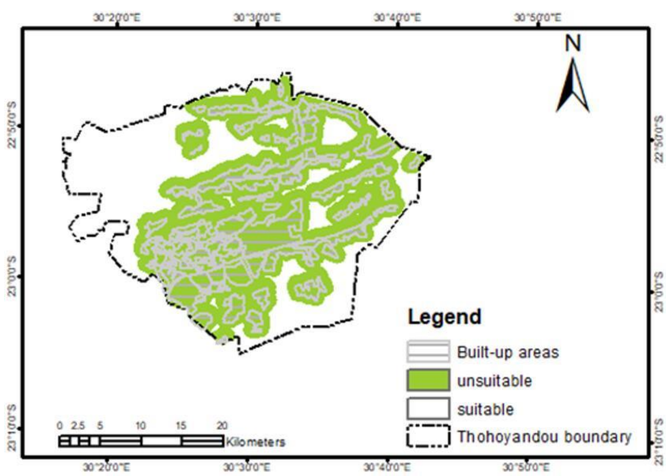

Figure 5. The built-up areas of Thohoyandou town
Source: Author 2021

3.1.5 Suitability against soil

Some soil properties make landfill construction and maintenance safer and more cost-effective. Essential soil factors include: permeability, effective porosity and workability [20]. Soils containing high silt and clay contents, safeguard groundwater and are a more cost-effective way to build a landfill site [21]. Differently, in this study, were appropriate for landfill since they include a combination of sand, silt and clay. Clay and silt soils, on the other hand, are less abundant in the study area. Tomlinson [22] emphasizes if clay is absent, it must be transported to the site or replaced by a geosynthetic system to ensure water quality. As a result of this criteria, Figure 6 indicates that chromic luvisols cover 94% of the study area and are judged suitable, whereas ferralsols cover 6% of the study area and are regarded unsuitable.

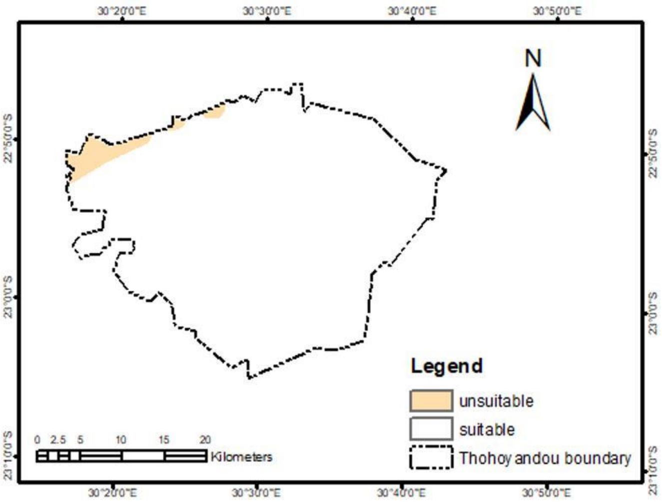

Figure 6. Soil suitability map of Thohoyandou town

3.1.6 Suitability against land use/land cover

A landfill site should be in a low-density population area and forest land to consider the land use/land cover natural values of the area [23]. It is recommended to choose property for a landfill site that is occupied by bare grass and wooded areas [24]. Hence, Figure 7 indicates that grasslands occupy a considerable portion of the area, accounting for around 45%, forest for 42% and mixed land use for 13%. Regarding the land use suitability criteria, the largest part of the study area 45% was judged highly suitable for landfills, while 42% was suitable and 13% was unsuitable.

3.2 Identification of possible suitable locations for a landfill site

Each unique variable within the study area was overlaid to create the reclassified maps. Based on the examined parameter, this process developed a reclassified map that indicates the potential suitable sites for establishing a landfill site versus the unsuitable areas. The eight reclassified maps, including rivers and dams, roads, built-up area, slope, lithology and soil type, land use/land cover and nature reserve were merged using the Boolean method "And" to produce the Final MCE suitability map shown in Figure 8.

According to the findings of the multi-criteria assessments, the existing landfill site in Thohoyandou town was found to be unsuitably located owing to critical variables. However, Leao et al. [25] in his landfill suitability study, obtained the same results after he performed Multi-criteria evaluation. The resulting map, based on the major variables, has identified several locations which are acceptable for constructing suitable landfills which may be utilized in the future. Figure 8 depicts several landfill sites which are suitable. All places marked with a yellow colour tag can be used as landfill sites. A total of almost 5 potential sites were identified. Even though the locations were considered acceptable, a ground assessment was required, in which the stated criteria were examined based on what was found on the ground.

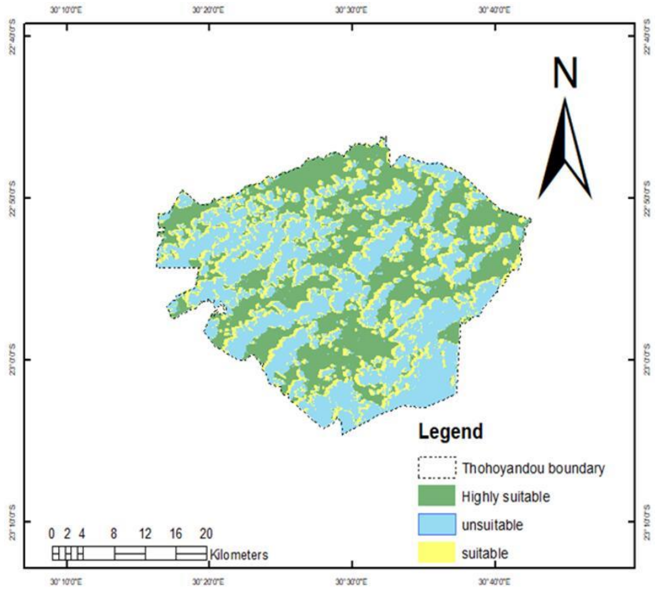

Figure 7. Land use/Land cover suitability map of the Thohoyandou town

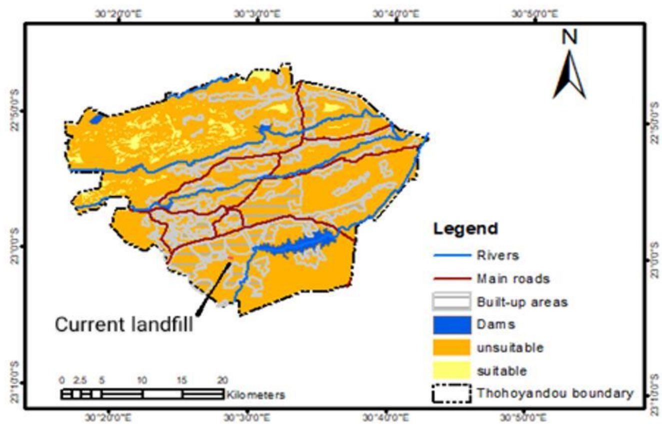

Figure 8. An overlay of all buffered parameter

3.2.1 Weighted overlay analysis

An assessment of the various sites focuses on environmental, social and economic effect was carried out to ascertain a suitable landfill site for the study area. The perceived significance of individual variable for all variables (slope map, lithological map, soil map, road map, river map, land use/land cover map and built-up area map) has been evaluated using the weight calculation. As a result, unique weights allocated to all variables depending on their effect on the wider environment. The greater weight a variable had, the further essential it was in the overall utility. The weights were calculated by doing a sequence of pairwise evaluations of the proportional relevance of the variables in determining pixel's suitability for the task under consideration.

On a 9-point continuous scale, weight ratings were assigned depending on pairwise comparisons. The scores that add up to 1 were calculated using these pairwise comparisons. The value of reclassification maps increased; river factors were increasingly important to establish an overall suitability map [26]. As illustrated in Figure 9, the overlay analysis and Weighted Linear Combination technique of accumulation resulted in six categories of suitability: extremely suitable, very suitable, suitable, moderately suitable, less suitable and unsuitable.

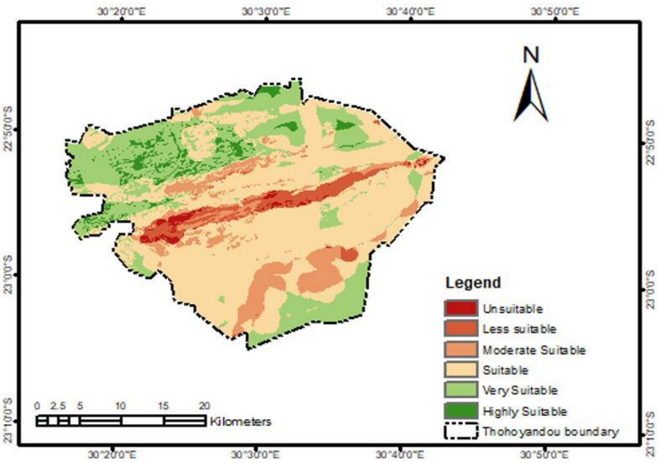

Figure 9. Weighted overlay analysis map

Figure 9 shows that around 5% of the entire area of the study area falls under very suitable class because the location meets the environmental, social and economic requirements. Built-up area, surface water, land use/land cover, soil, slope and road network are some of the factors to consider. The northern parts of the study area have a lot of potential landfill sites. The extremely suitable site accounts for 18%, suitable for 29%, moderately suitable for 20%, less suitable for 15% and unfit for landfill sites for the other 13%. According to this criterion, the northern part of Thohoyandou town is a highly suitable area for a land fill site (Figure 10). A weighted overlay study revealed that more sites were considered suitable, with only a tiny percentage of them being the most suitable.

3.2.2 Final suitability map

Imam et al. [27] used the Multi-criteria evaluation and weighted overlay analysis to find the most suitable sites. Similarly, in this study, further analysis was carried out such that the best suited sites were coupled with those discovered by Multi-criteria evaluation. The Boolean logic operator 'And' was utilized to combine the Multi-criteria evaluation suitability map and the weighted overlay analysis suitability map, creating a final suitability map in Figure 10 with all locations indicated by yellow colour codes as potential suitable sites. According to Figure 10, just 4.5% of Thohoyandou town is eligible for landfilling, whereas 95.5% is not.

Potential landfill sites (Figure 10) were further evaluated to help to determine the most suitable landfill site. Imam et al. [27] in his study, after combining Multi-criteria evaluation suitability map and the weighted overlay analysis suitability map, he conducted further analysis to identify the most suitable site for landfill of the study area among the five candidate sites based on their size, accessibility and significant distances from residents. Similarly, in this study potential landfill sites were subjected to further evaluation in terms of distance from the boundary, highway roads and size of the sites. Analytical Hierarchy Process (AHP) was used to evaluate the sites against all three criteria simultaneously. An overall suitability score was produced (Figure 11) for each potential landfill site allowing comparison and best-case selection.

Figure 11 shows that Landfill b (LFb) has the highest ranked suitable landfill site. Allen et al. [28] used Google Maps to further analyse his findings after using the AHP to ensure there were no unexpected factors prohibiting the landfill site from being established. Because of its ability to detect unforeseen components preventing the creation of the landfill site in the chosen area, the same scenario was employed in this study. The proposed landfill site was found to be suitable. As a result, the author proposed that LFb serve as the new landfill for Thohoyandou.

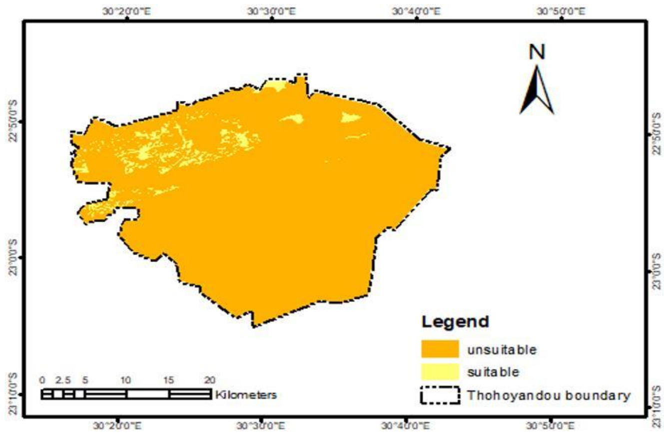

Figure 10. Potential landfill suitability map of Thohoyandou town

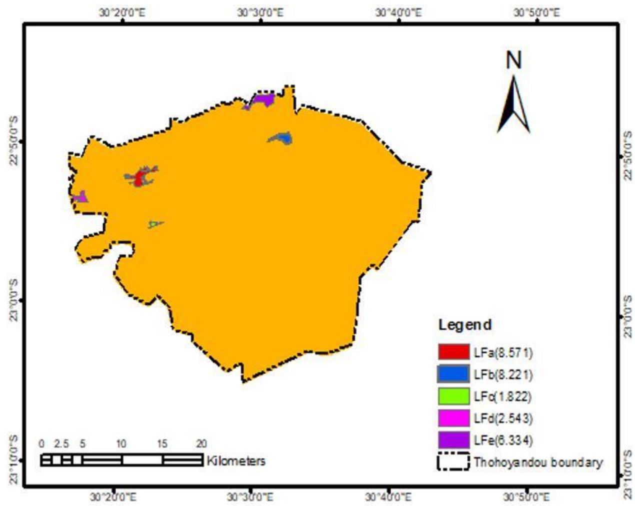

Figure 11. Suitable landfill sites in Thohoyandou town

3.3 Social impacts associated with current Thohoyandou landfill site

3.3.1 Air pollution and odour

Al-Yaqout et al. [29] found a relationship between landfill activities, air pollution and odour. He found that hydrogen sulphide was a significant source of landfill odours. Similarly, according to the questionnaires distributed in this study, 80.5 percent of participants said that foul odour was linked to their present poor health. The peak of series of frames is noticed at night, according to 35% of those interviewed, pushing inhabitants to cover windows and doors, preventing cross circulation at home. Managerial incompetence of the landfill-by-landfill operators, such as improper compression of waste dumped in the landfill, is the cause of air pollution and unpleasant odours. Nevertheless, pungent odours and air pollution can be minimised by properly covering solid waste immediately after its deposited in the landfill.

3.3.2 Dust and smoke

The landfill site has been known to frequently result in fire outbreaks owing to combustion, which are occasionally triggered by the squatters that reside on the landfill site. Whenever the landfill site is burning, 70% of the respondents acknowledged that the region is uninhabitable because smoke would cover entire section of Block J's residential area. According to the replies, the smoke from the landfill site is linked to respiratory ailments, chest difficulties and lung cancer. Similarly, dust particles from landfills were identified as a major source of worry in communities [30]. In his study, he discovered that people were infected with diseases caused by dust from a landfill.

3.3.3 Noise

Ninety-three percent (93 percent) of those questioned said they were bothered by the sound emitted by the Thohoyandou landfill as municipal trucks discharged of waste at the landfill. According to the results of a questionnaire survey, 65% of respondents believe that municipal waste disposal trucks can get closer to suburban buildings. Inhabitants revealed that, despite filing complaints about the issues, nothing is being done to mitigate their effects. On the other hand, Al-Ansari [31] indicates that noise can come from a variety of sources, not just the landfill. However, it is difficult to deny the heavy trucks and bulldozers in a dumpsite. He stated that due to a shortage of funds, the study area lacked enough bulldozers and heavy trucks.

3.3.4 Pests

Flies and mosquitoes were also identified as a major social issue associated with the Thohoyandou Block J landfill site [31]. Participants named malaria as one of the most common diseases afflicting Thohoyandou Block J residents. According to 85% of respondents, the existence of bodies of water and canyons at the landfill site, serves as a breeding site for mosquitos, resulting in the spread of malaria in the study area. Thirty-two percent (32%) of respondents stated that pests had devastated their farms and they believe the rodents came from the landfill site. The residents also mentioned the pools as a safety hazard due to the unprotected nature of the landfill site. Similarly, Nishanth et al. [32] documented fifty-five (55) cases of malaria that were linked to mosquito breeding from a nearby landfill.

3.4 Hypothesis test results

A chi-square test was employed to access whether the differences noted between the ratings on the significance of the social impacts and wellbeing of Thohoyandou residence were statistically significant ($p<0.05$). Based on the Chi-square results, the test revealed that no differences were found to be statistically significant for all six variables. The value of Pearson Chi-square obtained was 6.488 and P value is 0.024 thus the researcher accepts alternative hypothesis (H1) and rejects null hypothesis (H0) because P value is less than 0.05.

4. CONCLUSIONS

This study was carried out to identify the most suitable landfill site and pointing out social problems caused by the landfill site. The study applied GIS and RS methods to identify the most suitable landfill site by merging six maps in the study area which include: proximity to road networks, land use/land cover, slope, soil, built-up areas and surface water. According to the overall landfill suitability map, 4.5 percent of the overall study area is classified as suitable for the development of a landfill site, with several suitability scores varying from extremely suitable to suitable. Further assessment was performed in ArcMap to select the best suitable landfill site for Thohoyandou town from the five possible landfill sites depending on their size, distance from the major roads and distances from the town boundary.

A landfill site attained the highest rankings was chosen as the best landfill site for Thohoyandou town. Results of this study indicated that the problem of distance to built-up areas is not being recognized, since buildings are just few meters from the present landfill site. The landfill site emits terrible odours and serves as a recruiting place for mosquitos and flies, as well as being responsible for illnesses such as cholera, malaria and cancer, as mentioned by the stakeholders interviewed. Based on the negative impact of current landfill site, the authors highly advise the TLM's administrative body to implement the findings of this study as quickly as possible. The current research of the landfill site was limited to non-hazardous wastes. Hazardous waste must not be put at these locations since it requires separate specifications and site architecture than non-hazardous waste.

DATA AVAILABILITY STATEMENT

The data that support the findings of this study are available on request from M.Macheta. The data are not publicly available due to privacy or ethical restrictions.

ACKNOWLEGEMENTS

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