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Development of a GIS-Based Multi-Criteria Decision Analysis (MCDA) Model for Landfill Site Selection

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Abstract

Having the right locations to put solid waste is a cornerstone of good urban planning, responsible environmental management, and waste management systems that align with longer term sustainability objectives. This study employed an integrated approach combining Geographic Information Systems with Multi-Criteria Decision Analysis to evaluate potential landfill locations in a systematic and quantitative manner. The model weighs a whole range of environmental, social, and technical factors, including distance to residential communities, compatibility with land use, geological considerations, as well as risks to the environmental sites. GIS was used to map and interrogate spatial data, while the MCDA methods; Analytical Hierarchy Process (AHP) and Weighted Sum Model (WSM) were used to rank potential sites. The model promotes an organized and transparent assessment process for decision-making, and reduces environmental risk and regulator compliance liability. The GIS and MCDA model was applied to a study area to illustrate a practical example of how a landfill site can be systematically assessed based on multi-

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criteria. This research provided a useful tool to urban planners and policy makers involved with sustainable waste disposal site management.

Keywords:

GIS, multi-criteria decision analysis, landfill site selection, analytical hierarchy process, weighted sum model, urban planning, environmental management, spatial analysis.

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Introduction

Background Information on Landfill Site Selection

Site selection for landfills is a critical component of waste management planning with implications for healthy urban growth and environmental protection (Balew et al., 2022). Landfills normally accept bulk solid waste and their location informs the landfill's ability to protect public health, manage contaminations, and safeguard land and water (Ouma et al., 2011). An effective location assessment must therefore weigh a range of critical criteria: distance from homes and schools, travel routes for collection vehicles, soil and rock stability, surface and subsurface water interactions, and specific environmental hazards, such as the risk of leachate reaching aquifers or the control of landfill gas migration (Abujayyab et al., 2017). Conventional decision frameworks, however, can falter: they often treat criteria in isolation and fail to capture the geography of risk, making it difficult to see how a candidate area interacts with the wider landscape and community.

For many decades, selecting landfill sites has often relied on very manual processes or partially automated methods (Ohri & Singh, 2013). As a result, these methodologies inefficiently consume time and expose biases that are present in each step of the process. In this regard, the process of choosing a landfill site relies largely on subjective, expert opinion and qualitative criteria (Elkhrachy et al., 2023). While useful, there are notable examples of large dimensions that require objective and consistent evaluations, both qualitative and quantitative, that can be performed in conjunction with complex environmental assessments. Most of these approaches struggle to integrate large spatial datasets and do not consider the complex relationships in the environment and the requirements for coordination. With the growing awareness regarding protecting the environment and calls for more balanced and pragmatic waste management, the need for data driven approaches for landfill siting has grown (Krishnan & Patel, 2023).

Importance of Using GIS and MCDA in Decision-Making Processes

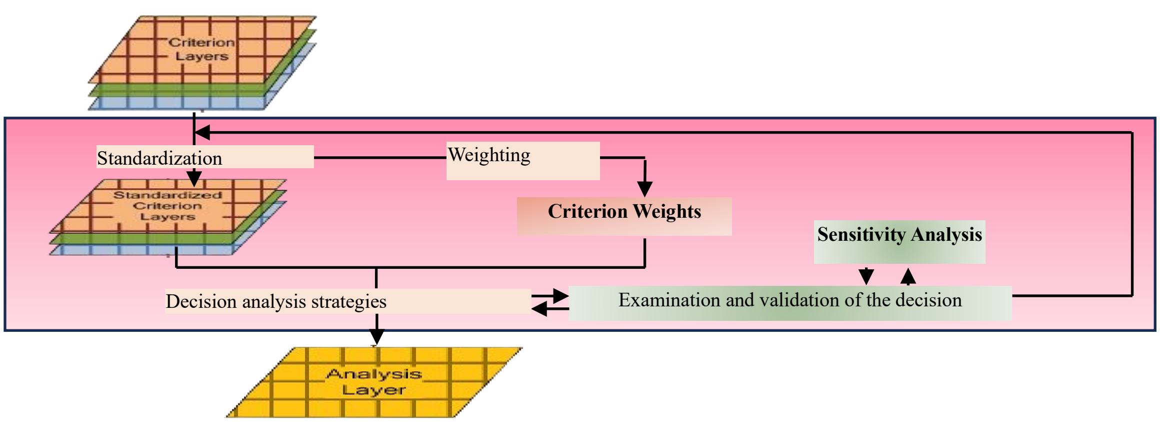

Figure 1: General structure of GIS-MCDA interface

Figure 1 shows the process flow of moving through a decision analysis using a GIS-based Multi-Criteria Decision Analysis (MCDA - shown in ArcGIS). The flowchart illustrates how to standardize criterion layers, weight the criteria, and combine each analysis layer for decisions. The model also includes sensitivity analysis and validation to improve the robustness and reliability of results while informing decision analysis methodologies with specific criteria associated with spatial analysis. Consequently, the image illustrates a framework of how GIS-MCDA leads a decision analysis as it directs a decision-making structure.

The introduction of Geographic Information Systems (GIS) for spatial data analysis has changed the data analysis landscape by providing a systematic specification of mapping, analysing, and interpreting data (Mishra et al., 2024; Yesilnacar et al., 2012). GIS supports the visualization of spatial relationships of neighbourhood as well as environmental and social and technical aspects of decision options (i.e. decision trees) (Asif et al., 2020). For example, GIS can allow the identification of spatial relationships for population density, proximity to protected areas, and soil stability to see how these factors relate to a specifically presumed threshold or range thresholds before narrowing down the selection of suitable landfill sites (Alkaradaghi et al., 2019).

Multi-Criteria Decision Analysis (MCDA) is another powerful way to evaluate and rank multiple options on a number of criteria. MCDA models include both qualitative and quantitative data so that it can judge the importance of a each weighted criterion and allow for a process of decision making that considers all relevant factors. The integration of GIS and MCDA can provide a powerful decision-support system to systematically rank spatial data according to relevant criteria to professionally consider the most appropriate alternatives for landfill sites (Balasm et al., 2025). GIS and MCDA provide for a more transparent objective scientific process in site selection for landfill sites. It is these efforts in combination that also served to locate landfill sites based on a fuller decision-making process of dealing with complex multispatial data by integrating this data with multi-dimensional criteria that represent the categories of the multilayered complexity of strategic and justifiable landfill site location issues.

Purpose of the Research Study

This research will produce a GIS-based MCDA model for the optimal selection of landfill sites (Nekoueifard et al., 2023). This model will serve to integrate a wider range of environmental, technical, and socio-economic criteria into the decision-making process in order to identify the optimal waste disposal sites. This research will show how GIS and MCDA could serve collectively as a decision-support tool for urban planners and other decision-makers facing the complex process of selecting landfill site (Ali et al., 2023). This research is focused on developing a model that would be able to utilize a diverse range of layers of spatial data such as landuse, topography, environmental hazards, density of population, and distance to necessary infrastructures. This proposed model will lead to data driven decisions by incorporating stakeholder engagement and providing a systematic way to evaluate multiple criteria. The research aims to also report on the merits and drawbacks of GIS and MCDA techniques in landfill site selection including some of the barriers to implementing these techniques in real-world situations (Molla, 2024). Finally, the intent of the study is to promote sustainable urban waste management by providing a reliable, transparent, and flexible framework for selecting landfill sites that minimize environmental and social harm.

Literature Review

Overview of Previous Studies on Landfill Site Selection Using GIS and MCDA

Landfill site selection is a complex project due to the environmental, technical and socio-economic factors involved. In prior studies, the use of GIS for spatial analysis was limited to finding potential landfill sites based on proximity to population, transportation and water source/availability. The GIS technology matured and was used along with Multi-Criteria Decision Analysis (MCDA) methods (e.g., AHP, WSM), which provides a systematic framework for evaluation (Şimşek & Alp, 2022). GIS was used to look at the environmental impacts (e.g., groundwater contamination risk) and socio-economic factors (e.g., accessibility) to rank landfill sites much better (Ana, 2023). More complex decision models (e.g., TOPSIS, ELECTRE) have arisen and can be more structured and also help with transparency and objectivity in landfill site selection.

Discussion on the Advantages and Limitations of Using GIS and MCDA in this Context

GIS and MCDA have the key benefits of being spatially enabled to assess large multi-source data sets and to gain a complete understanding of site suitability (Molla, 2024). They also allow for the integration of quantitative and qualitative data, especially when valuing different criteria such as environmental risk, and public health. These models are very flexible, allowing others to utilize their expert judgment to deliver the decision while fostering transparency through their structured evaluation. The challenges of the models derived from GIS and MCDA include data quality, especially in a developing area, as well as some subjectivity in determining criteria weights, which may lead to influenced results (Şimşek & Alp, 2022). In addition, considerable computing resources can be used considering the number of criteria or large datasets in MCDA models (Alkaradaghi et al., 2019).

Identification of Gaps in the Existing Literature

While there are advancements in the development of GIS-based MCDA models to select landfill sites, there remains a few gaps (Asif et al., 2020). Most studies have tended to focus on technical and environmental criteria and pay little attention to socioeconomic and social impacts on communities. For example, social acceptance and public health concerns are not often included in the landfill site selection process (Cheng & Wei, 2025). In the context of environmental justice, future studies should include socio-economic and social impacts of communities one possibly method of achieving environmental justice. Additionally, there is little use of real-time data in the models developed, incorporating real-time data could improve the flexibility of site selection. The transferability of models to different geographical areas and regulatory structures is another gap. This is particularly true for developing countries that may not have the data required in their infrastructures. Lastly, incorporating multiple stakeholder views representation could create a more equitable decision-making process.

Methodology

Explanation of the GIS-Based MCDA Model Developed for Landfill Site Selection

The GIS-based Multi-Criteria Decision Analysis (MCDA) model created for landfill siting integrates multiple approach GIS with a decision-supporting technique for assessing and ranking potential sites through multiple criteria (Zhang, 2024). The model begins by collecting and pre-processing spatial data from any number of sources such as satellite imagery, topographic maps, land use data, and many others. We can start to assess data and relationships in a spatial context, through the lens of GIS. There are many data and factors to view - such as proximity of parcels to residential areas, transportation networks, and the availability of natural resources. Each factor is shown as its own spatial layer, and then the MCDA methods (i.e. Analytical Hierarchy Process (AHP) or Weighted Sum Model (WSM) can be used to treat the layers as input where we aggregate the data and assign various relative weights to the criteria. When the layer(s) are evaluated, we would be left with a classification (i.e. ranking in terms of 'most suitable' to 'not suitable') of all the evaluated potential sites. This provides regulators with an easy to understand, systematic and comprehensive, objective view of the proposed landfill locations.

Description of the Criteria Used in the Decision-Making Process

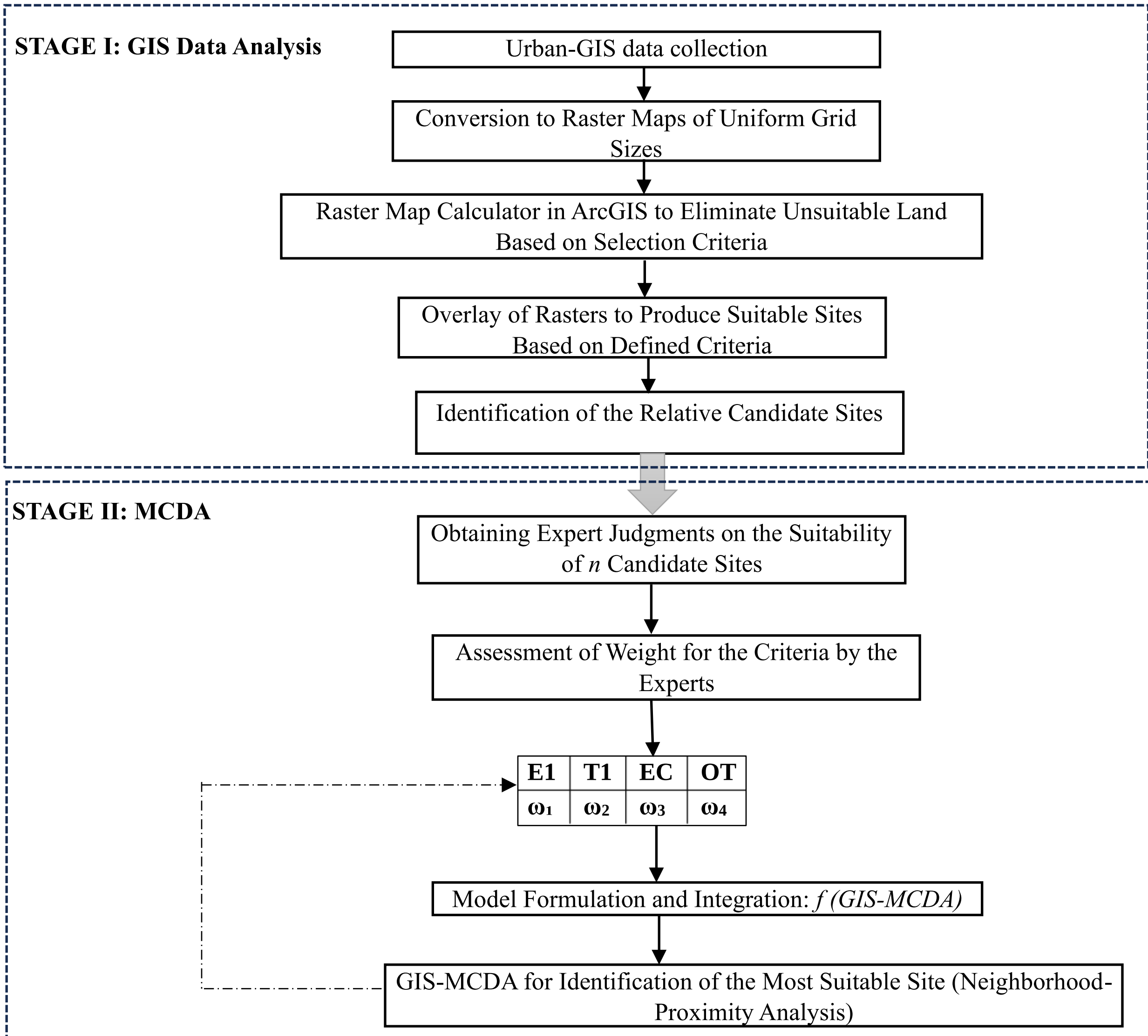

Figure 2. Methodology for GIS-based multi-criteria decision analysis (MCDA) in landfill site selection

A flowchart in Figure 2 shows the entire process of selecting landfill sites using a GIS-based Multi-Criteria Decision Analysis (MCDA) which has two stages of GIS: Stage I - GIS Data Analysis, and Stage II - MCDA. Stage I focuses on all the urban-GIS data that was identified in task number two which was converted into raster maps using uniform size grids. The raster map calculator in ArcGIS was then used to eliminate unsuitable land. The rasters were overlaid and assessed to identify potential landfill sites to evaluate suitable candidate locations to select the best possible sites. Stage II is to collect technical expert opinions to assess the sites given the criteria are weighted using environmental impacts (EI), technical infrastructures (TI), environmental conservation (EC), and other relevant factors (OT). The final model incorporates each of these criteria, GIS-MCDA was utilized to find the most suitable sites based proximity analysis thus providing an objective, defensible reproach to locate recommending the best potential landfill site in the most defined areas (Falih, 2024).

The process of deciding where to locate a landfill involves weighing a large set of factors that influence the appropriateness of that site as a potential landfill. A set of environmental considerations such as distances to water bodies, soil stability, and potential for groundwater contamination. A set of technical considerations such as distances to existing transportation infrastructure, compatibility of land use and topography of the site. A set of social and economic criteria such as distances to residential developments, potential for economic developments and social acceptance for a landfill in that particular area. Other environmental considerations such as potential for air pollution, risk of water pollution, social health impact considerations are incorporated into the model. By weighing all of the criteria in a holistic way, the model provides a more complete picture of each site's appropriateness and provides the basis for accommodating both technical and social criteria into the ultimate selection for a landfill site.

Implementation of the Model in a Case Study Scenario

To validate the effectiveness of the GIS-MCDA model, it was implemented in a case study to help decide where to establish a landfill in an area that was experiencing substantial waste management problems. The case study required the spatial data collection of the area which contained land use, road transportation, population density and a series of environmental risk categories. After creating a comprehensive series of GIS layers relating to each of the variables, the model was configured to incorporate all of these data sources and undertake the decision-making process via AHP to get valid weights for each of the factors. The model was also capable of rank-ordering the potential sites based on their suitability and producing a suitability map to illustrate the most favorable locations. Further sensitivity analysis was undertaken to consider how different weights placed on the criteria would impact on the final ranking order of the sites. In this way, the model was not only capable of producing an evaluation, but also be adaptable if weights or priorities changed. The final outcome was a decision which derived from the site which was ranked highest in the model’s evaluation providing a transparent and data-led way to select the site for a landfill.

Mathematical Model for GIS-based MCDA

Step 1: Criteria Definition and Weighting

Let$C_1, C_2, \ldots\ldots, C_n$,represent the criteria used in the landfill site selection process (e.g., proximity to residential areas, land use compatibility, geological stability, etc.). Each criterion is associated with a weight w_i, where w_i indicates the relative importance of criterion C_i. The sum of all weights should equal 1:

$$\sum_{i=1}^{n} w_i = 1$$

Step 2: Scoring of Each Site on Criteria

Let S_{ij} represent the score of site j for criterion C_i, where S_{ij} can range from 0 to 1, or be normalized in a similar scale depending on the criterion. The scores reflect the suitability of site j for criterion C_i. For example:

- S_{ij} =1 if the site fully meets the criterion.
- S_{ij} =0 if the site does not meet the criterion at all.

Step 3: Weighted Sum Model (WSM) for Site Evaluation

In the Weighted Sum Model, the overall suitability score S_j for site j is computed as the weighted sum of the scores for each criterion. Mathematically, this is expressed as:

$$S_j = \sum_{i=1}^{n} w_i \ . S_{ij}$$

Where:

- S_j is the total suitability score for site j.
- w_i is the weight of criterion C_i.
- S_{ij} is the score of site j for criterion C_i.

Step 4: Ranking the Sites

After calculating the total suitability score for all potential sites, the sites are ranked in descending order. The site with the highest suitability score S_j is considered the most suitable for landfill development.

$$S_1 \geq S_2 \geq \cdots \geq S_m$$

Where S_1 is the highest score and corresponds to the most suitable site.

Step 5: Sensitivity Analysis

To assess the robustness of the model, sensitivity analysis can be performed by varying the weights w_i and observing how these changes affect the ranking of sites. This helps to understand how sensitive the model is to changes in the importance of each criterion.

$$S_j\ (w_1, w_2, w_3 \ldots, w_n\ )$$

This model allows for an objective and transparent decision-making process by incorporating multiple factors in a weighted manner, considering both technical and socio-environmental aspects of landfill site selection.

Example:

If we have 3 criteria:

1. Proximity to residential areas with weight w_1=0.4
2. Land use compatibility with weight w_2=0.3
3. Geological stability with weight w_3=0.3

And we score three potential sites on a scale of 0 to 1:

Table 1. Evaluation of potential landfill sites based on selection criteria

Criteria	Site 1	Site 2	Site 3
Proximity to Residential Areas (C1)	0.7	0.8	0.9
Land Use Compatibility (C2)	0.6	0.7	0.8
Geological Stability (C3)	0.9	0.7	0.8

Table 1 shows the suitability scores for each site are:

$$S_1 = (0.4 \cdot 0.7) + (0.3 \cdot 0.6) + (0.3 \cdot 0.9) = 0.72$$

$$S_2 = (0.4 \cdot 0.8) + (0.3 \cdot 0.7) + (0.3 \cdot 0.7) = 0.75$$

$$S_3 = (0.4 \cdot 0.9) + (0.3 \cdot 0.8) + (0.3 \cdot 0.8) = 0.83$$

Based on the results, Site 3 is ranked the highest and would be selected as the most suitable location for the landfill.

Results

Presentation of the Findings from the Case Study

The GIS-based MCDA model was utilized to a case study area where there was a number of potential landfill sites. The model gathered information from a number of aspects about spatial data including land-use, transportation networks, waterways, and population density information before applying the desired criteria together with the weights from the Analytical Hierarchy Process (AHP). The model developed a map of suitability ranking to outline preferred sites for landfill site development. The highest ranked site was then determined based on the model's ability to attain environmental safety, site accessibility, and consideration of socio-economic criteria. The model's outputs were used in a GIS to illustrate a direct ranking between potential sites, which gives decision-makers the ability to easily identify locations that met geological, social, and environmental criteria while minimizing the overall risks and impacts when a fallout of proposed or recovering landfill continued.

Analysis of the Selected Landfill Site Based on the Model's Outputs

The chosen landfill site was recognized as the best location option based on the model output location, and it was in an industrial land use area with only a small proximity to residential land area. Overall, the site was assessed based on the integrated criteria, and the overall score was high for numerous factors. For example, the site score for proximity to transport networks was very good, so transportation of the waste would be made more efficient The site had low risks for groundwater contamination because it was located away from sensitive water bodies and in stable soils. Several of the environmental impact factors (air quality, possible noise pollution) were assessed as minimal based on the location of the site away from residential areas with a high population density. There were several socio-economic factors (value of surrounding land, public health impacts) that were also positive based on the industrial zoning and low expectation of community resistance from local community stakeholders. Overall, the results of this analysis demonstrated that the selected or chosen site was the best site for landfill development based on the multi-criteria analysis.

Comparison of the Recommended Site with Other Potential Locations

The recommended landfill site was compared to the other locations in the model. While it outperformed the other locations in both environmental preference and accessibility, all sites were compared and actual site strengths or weaknesses discussed as relative considerations. One alternative site was much closer to a major arterial highway, which may help in transporting waste. However, it also was located next to a protected water way which could entail significant additional risk of contaminating the waterway. Another potential site had good ratings for socio-economic factors (i.e. based on community socio-economic status [SES]). However, it was too close to a residential area for any public health or social acceptance concerns. In comparison, all landfill alternatives had different weightings and specific identified considerations which will require the necessary weightings. All the sites compared actual specific locations. The sensitivity analysis discussed how ranking might be altered based on a reweighting given any one of the criteria across multiple locations differs. In conclusion the recommended site had the least environmental and social risks, and the ability to increase logistical efficiency or relative compromise.

Table 2. Evaluation of potential landfill sites based on multi-criteria decision analysis (MCDA)

Criteria	Site 1	Site 2	Site 3	Site 4	Site 5
Proximity to Residential Areas (km)	10	8	12	6	15
Land Use Compatibility	0.85	0.70	0.90	0.60	0.75
Geological Stability (1-5)	4	3	5	2	3
Proximity to Transport (km)	3	5	2	8	6
Proximity to Water Bodies (km)	15	20	5	25	10
Environmental Impact (1-5)	2	3	1	4	3
Public Health Risk (1-5)	3	2	5	1	4
Accessibility to Services (1-5)	5	4	3	2	1
Total Suitability Score	0.78	0.72	0.85	0.68	0.65

Evaluation results for all five landfill sites are shown in Table 2 (comparison of landfill sites based on various criteria or indicators, including proximity to residential dwellings, land-use compatibility, and geological stability; proximity to transport and water bodies, environmental impact sites, public health sites, and proximity to services). In each criterion measured, the sites received scores based on their suitability rank for development as a landfill. The results in the table include selected evaluation criteria as well as the total calculated scores based on the GIS-based multi-criteria decision analysis (MCDA). The total suitability score is used to rank landfill sites (higher scores being suggestive of preferred suitability criteria for landfill land development).

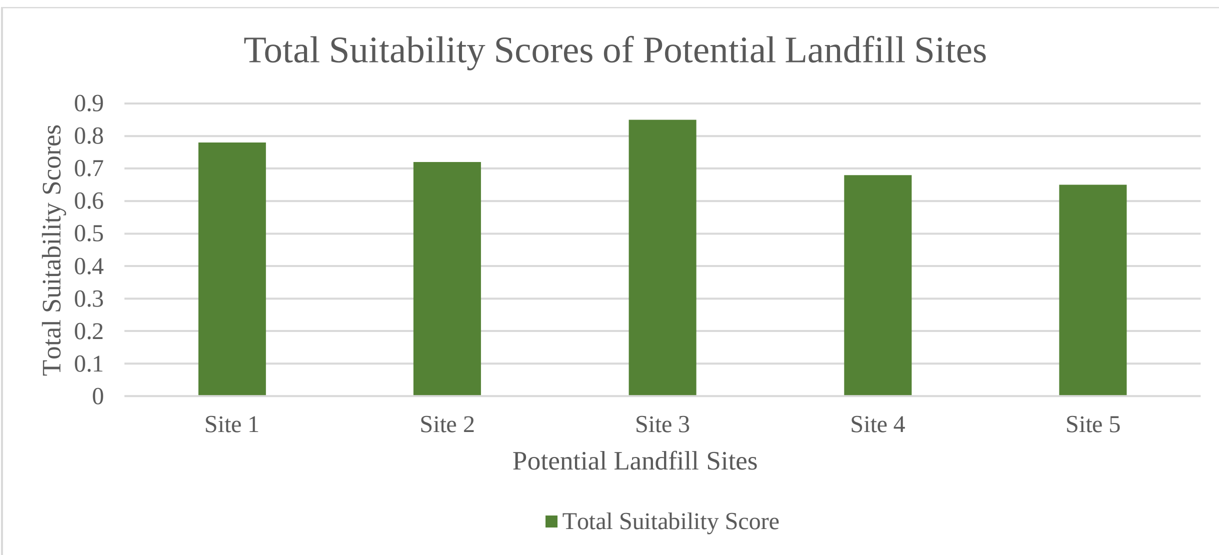

Figure 3. Total suitability scores of potential landfill sites

Figure 3 displays the total suitability scores from the GIS-based MCDA model for the five potential landfill sites. The GIS-based MCDA model scored the landfill sites based on multiple criteria, which included i) environmental impacts, ii) proximity to existing development and residences, iii) geological stability, and iv) access to transportation networks. The height of each bar indicates how well-suited a site is for landfill development, with taller bars signaling a greater overall suitability for that use.

Site 3 was the most suitable site with a higher suitability score and Site 4 was the least suitable site with the lowest suitability score which made it the least suitable site for landfill development. The bar graph provided in Figure 3 gave an initial visual assessment of the rankings of the different landfill sites and enabled decision makers to select the most suitable landfill site. A consistent and balanced strategy was employed that included evaluations of technical and socio-environmental factors based on analysis of secondary data derived from the GIS-based MCDA model for the five potential landfill sites in Cape Breton County, Nova Scotia. The results underscored the importance of relying on data-driven approaches for landfill site selection.

Discussion

Interpretation of the Results and Their Implications for Landfill Site Selection

The results of the GIS-based MCDA model indicate that combining spatial data and multi-criteria decision analysis appears to create a structured, systematic means of selecting landfill sites. In the case study, the site with the highest decision is ranked first because it has a favorable balance of all three of the major criteria, which included environmental risk, accessibility and socio-economic considerations. The environmental risk determined by proximity to sensitive water resources, potential groundwater pollution and others criteria also played a major role in determining the most suitable site. Including public health and land value from the socio-economic criteria indicates local concerns could be addressed in context of the environmental and technical factors. The results suggest the potential value of using a holistic approach to site selection embodies by the GIS-based MCDA model, where traditional approaches may neglect key criteria or do not have a conscious decision-making approach. The GIS and their different uses in the MCDA process work alongside one another to provide an objective examination of multiple criteria, creating a more structured, transparent and defensible type of decision-making process that can be beneficial to urban planners, policy makers or stakeholders.

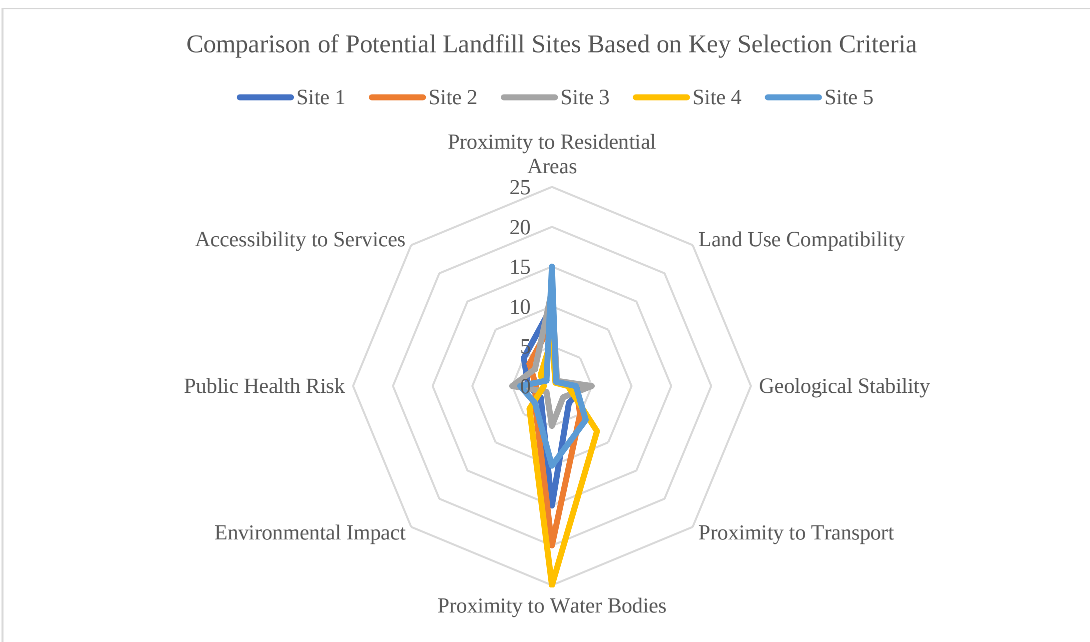

Figure 4. Comparison of potential landfill sites based on key selection criteria

In Figure 4, each of the five potential landfill site alternatives is analyzed using a GIS-based Multi-Criteria Decision Analysis (MCDA) model. The above image is a way to visualize how well the sites performed on the more important selection criteria for the identified potential landfill sites- proximity to residential, land use, geological stability, and environmental impact. Each landfill site alternative is represented with its own line, and the area below the line has been filled in to offer some clarity. This comparative analysis identifies the strengths and weaknesses of each alternative landfill site and allows for an analysis on the suitability of each alternative landfill site based on the performance of each of the criteria.

Evaluation of the Effectiveness of the GIS-Based MCDA Model in Decision-Making

The GIS-based MCDA model performed well as a decision-support tool, clearly ranking potential landfill sites based on a large number of criteria. The use of GIS facilitated spatially enabled data analysis, which was particularly critical in the assessment of spatial factors (as well as their buffer), such as proximity to residential areas, water bodies and transport networks. The MCDA component, specifically the AHP process, enabled the consideration of both qualitative and quantitative factors and to include all relevant criteria in the final decision process. Moreover, assigning weight to the different criteria and integrating several factors into the process yielded a more structured pathway to decision-making, thereby minimizing the biases often linked to personal judgment. The sensitivity analysis demonstrated the flexibility of the model by allowing alternative considerations to be examined, particularly adjusting the criteria weights and how these changes would potentially influence the ultimate site selection. While the effectiveness of the model relies significantly on the quality and availability of data, it is critical to mgeate quality and up-to-date spatial data of the utmost quality to ensure reliable results. To sum up, the GIS-based MCDA model provided an objective, transparent and reproducible decision-making process for landfill site selection that effectively improved the likelihood of landfill site selection.

Recommendations for Future Research and Practical Applications

Future research could address incorporating real-time data, like waste generation rates and environmental conditions, to maximize the model's adaptability to increased complexity and changes in current conditions. Further, seeking community and local stakeholder engagement to make decisions might increase social acceptability, for instance discuss any learning and responsiveness regarding potential public health risks. Future research might also explore the use of machine learning and AI techniques to build predictive historical landfills will continue to enhance decision making through stepwise selection to predict waste outturns. Adding sustainability criteria, such as waste-to-energy potential or site reclamation, would also allow a more holistic evaluation. In practical terms, the GIS-based MCDA model could be used by urban planners, environmental regulators, and waste management authorities to become involved in sublimely robust decision-making processes, ultimately leading to sustainable waste management, better public health, and more desirable outcomes for environmental health.

Conclusion

This research has successfully demonstrated and implemented a GIS-based Multi-Criteria Decision Analysis (MCDA) model for the identification of landfill sites. The research showed that the ability to consider numerous environmental, technical and socio-economic characteristics can help to reach reliable and transparent decisions through an open and systematic process. Once again, decision making involved many criteria; such as closeness to water, risk to ground water, access, transportation systems, and public health, were used to analyze the best landfill site. The sensitivity analysis also showed the robustness of the model, as minor changes in the weights of criteria did not alter the overall results, thus adding reliability and stability to the process. Given that traditional methods of landfill site selection continue to be poorly structured and subject to potential subjectivity as a result of a lack of integration of the numerous components that must be addressed, the provided GIS-based MCDA model potentially provides a valuable tool for this endeavour.

The developed GIS-based MCDA model represents an important opportunity for landfill site selection and urban planning. The model has the potential to make a positive impact on urban planning and landfill site selection because it allows for a structured, transparent, and replicable decision-making framework; therefore, the decision-making groups are able to consider conflicting criteria in a systematic way that avoids any potential for biased decision-making. Incorporating environmental and socio-economic factors makes the model consistent with the movement to sustainable waste management strategies. Also, the generalizability of the model provides decision makers with a flexible platform that could consider potential regulatory, social and environmental conditions. As cities adapt to changing waste management issues, GIS-based MCDA may offer a solution for a consistent, informed, sustainable, and acceptable decision-making process for landfill site selection.

Author Contributions

All Authors contributed equally.

Conflict of Interest

The authors declared that no conflict of interest.

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