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Analyzing and Mapping Suitability Landfill Site Selection in Khartoum State, Sudan using GIS-based MCDA

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ABSTRACT

The issue of landfills represents a significant environmental challenge for the establishment of safe and healthy communities within Khartoum State, Sudan. The analysis of landfill suitability constitutes one of the most pivotal environmental concerns, governed by a multitude of restrictive criteria. Within Khartoum State, which encompasses three localities, there exists no landfill site that has been established through scientifically rigorous processes. This study aimed to identify appropriate locations for solid waste landfills by employing a Geographic Information System (GIS)-based Multi-Criteria Decision Analysis (MCDA). Nine criteria were developed to form the dataset. GIS spatial analysis (MCDA) methodology was utilized to amalgamate the relative weightings assigned to each criterion through a weight overlay technique. Each criterion possesses a weight that indicates its relevance to the selection of landfill sites. The findings revealed the emergence of five classifications regarding the suitability of sites for landfill selection, ranging from areas with very high suitability to those with low suitability.

Keywords: *Landfill, Suitability analysis, GIS, MCDA, R S.*

Introduction

Landfill is characterized as the allocation of waste material onto or into terrestrial surfaces. This encompasses specifically designed landfill facilities as well as provisional storage exceeding one year at designated permanent locations. The definition encompasses both internal landfill operations, wherein a waste generator manages its own refuse disposal at the point of origin, and external landfill sites. From a spatial perspective, significant apprehension exists regarding the geographical placement of urban landfills. Landfill management represents a primary municipal responsibility that entails numerous construction activities and preliminary analyses aimed at determining optimal site selection. The identification of an appropriate landfill site at the state level, encompassing the three principal urban areas, presents a significant challenge for environmental sustainability, urban planners, and municipal authorities alike. The existing landfill location is deemed unsuitable, resulting in critical environmental issues that have provoked public demonstrations and complaints regarding associated health repercussions. Furthermore, the selection of landfill sites through suitability modeling within Geographic Information Systems (GIS) constitutes a paramount priority for the recovery and reform of municipal management systems. As far as the domain of solid waste management technology is concerned, Geographic Information Systems (GIS) and Remote Sensing (RS) represent viable integrated methodologies employed for the identification of appropriate sites for landfills or for the relocation of existing sites utilizing Multi-Criteria Decision Analysis (MCDA).

Remote sensing possesses the capability to furnish GIS with critical spatial data necessary for the formulation of criteria encompassing land use, land cover, topography, elevation, drainage systems, among others. In light of the current trajectory of urbanization in Khartoum, the establishment of multifunctional landfills is imperative for an urban environment that has developed without robust environmental governance. Prior investigations have demonstrated the efficacy of integrating geographical data (including land use, road networks, and slope) with computer vision techniques to enhance the identification of waste containers, thereby improving solid waste collection processes [11]; [13]; [14]; [18]. Geographical Information System (GIS) methods are employed extensively in suitability analysis, with numerous studies contributing to the assessment, evaluation, and analysis of appropriate solid waste landfill sites utilizing Multi-Criteria Decision Analysis (MCDA) within a GIS-based framework. Various studies across diverse disciplines have examined the landfill issue from multiple angles. Some investigations concentrated on the criteria and standards pertinent to landfill establishment, while others focused on impact assessments, and a growing number have recently incorporated spatial analysis techniques to evaluate and inform the suitability of landfill site selection. Several authors have integrated the spatial analysis capabilities of GIS with Multi-Criteria Decision Analysis (MCDA) into the site selection framework [12]. Site selection analysis constitutes a predominant focus in the scholarly literature regarding waste management and the identification of suitable landfill sites, [1]; [2]; ([3]; [4]; [5]; [10]; [12]; [16];

[17]; [20]; [21]; [22]; [23]. Numerous studies have explored waste management from various perspectives [7]; [9]. Effective landfill management plays a critical role in minimizing environmental impacts compared with uncontrolled dumping of municipal solid waste. Rather than serving merely as disposal sites, well-planned landfills require careful evaluation of location, infrastructure capacity, and environmental constraints. Site suitability analysis is a widely used spatial decision-making approach for identifying optimal landfill locations, particularly in regions where land availability and environmental sensitivity are major limiting factors. In Khartoum State, the selection of appropriate landfill sites represents a significant challenge due to rapid urban expansion, population growth, and competing land-use demands. The primary objective of this study is to address the spatial problem of identifying environmentally and socially suitable locations for solid waste landfill development within Khartoum State. The increasing emphasis on waste minimization, source reduction, recycling, and material recovery, landfilling remains the most commonly practiced method for municipal solid waste disposal. Across Khartoum State, residents in both urban centers and surrounding localities report growing concerns regarding the accumulation of solid waste on streets and open areas, often exceeding the daily collection and transportation capacity of existing waste management systems. Although an officially designated landfill system exists, its infrastructure is insufficient to accommodate the continuously increasing volume of waste generated across the state, highlighting the urgent need for scientifically guided site selection and improved landfill planning.

Problem identification

The research problem addressed in this study can be framed by the following question: why does the selection of an inappropriate landfill site pose serious risks to the environment? Poorly located landfills often result from inadequate scientific planning and insufficient consideration of environmental, social, and technical criteria. When site selection is not guided by systematic analysis, landfills may negatively affect surrounding ecosystems, groundwater resources, air quality, and nearby communities. Therefore, inappropriate landfill siting is not only an environmental concern but also a planning failure, emphasizing the need for scientifically informed and spatially optimized site selection processes. The processes such as leachate, toxins and spreading are the ones that causes environmental and community's unwanted negative effects. Urbanization and limited management of Khartoum City intensify the problem of Urban Solid Waste (USW) and its infrastructures. This created bad urban landscape image where there are huge of wastes accumulated everywhere haphazardly. Khartoum City just has a daily (4527) ton of solid waste that not cope with the solid waste service capabilities to be transported daily. Uncontrolled waste left an image of a considerable accumulated scattered point on streets that assessed the mismanagement history of the solid waste management in the capital of the country. Limited landfills and distance problem as well as low waste transportation service are contributed in the problem for disposing daily generated solid waste. The Khartoum municipality reported that not all the daily solid waste generated reached the landfill as this rate is higher than the operational capacity. In urban areas of Khartoum State, solid waste dumped in an open area and on the streets without any consideration to the adverse impact that will be generated.

It is clear that the solid waste problem in Khartoum states' cities is accelerated at a progressive rate due to mismanagement and increasing solid waste generation associated with urbanization growth. The problem of mismanagement let the people dump their waste in inappropriate places. In most developing countries, waste management is done by local authorities but different research has shown that these countries have insufficient and inefficient waste management systems [6]. The existing landfill locations for solid waste final disposal over Khartoum State is misallocated and caused many environmental and health problems. To think about the solutions of these problems, we need to introduce a modern spatial modelling in landfill site selection.

Study area

The study was conducted in Khartoum State, which comprises the three major urban centers of Khartoum, Omdurman, and Khartoum North (Bahari). Geographically, the state lies between longitudes 31.5°E and 34°E and latitudes 15°N and 16°N. Administratively, Khartoum State is divided into seven localities: Khartoum (the capital), Omdurman, Khartoum North, Sharq An-Nil, Jabal Awliya, Om Badda, and Karari (Figure 1). Khartoum State is the smallest state in Sudan in terms of area, covering approximately 22,142 km^2, yet it is the most densely populated, with a population of about 5.27 million according to the 2008 census. Population density varies considerably across the state due to uneven urban development and rapid expansion of residential areas, particularly within the main cities. The region is characterized by a semi-arid climate, marked by high temperatures and low precipitation. Annual temperatures range approximately between 24 °C and 48 °C, while the mean annual rainfall is typically less than 75 mm. Khartoum State occupies a strategically significant location at the confluence of the White Nile and the Blue Nile, placing it at the geographical and economic center of Sudan.

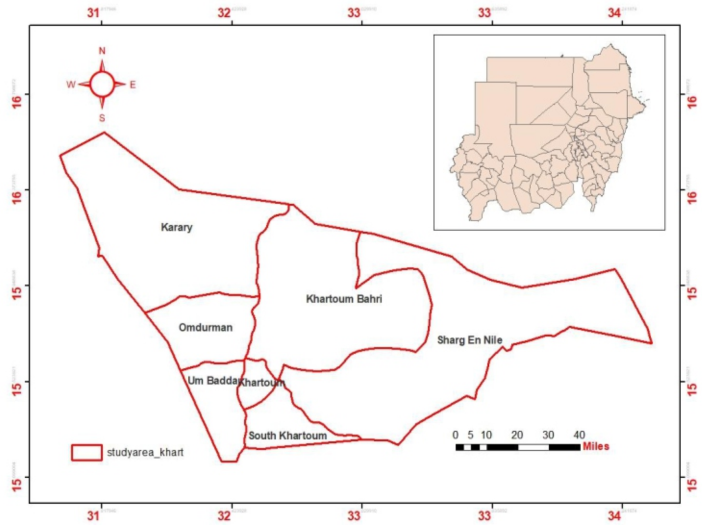

Fig (1): Study area – Khartoum State – Sudan

Methodology

To select landfill, the procedure goes into the needs to identify the suitability map. Within the advancement set of suitability analysis techniques that have been recommended in spatial analysis and evaluation, GIS techniques emerged for their capabilities and potentialities of spatial analysis solving problems (suitability modeling application). The analytical strategy adopted in this study is aligned with the overall methodological framework and involves the development of thematic maps representing the selected evaluation criteria, determination of relative weight factors, and application of a weighted overlay technique using a Multi-Criteria Decision Analysis (MCDA) approach. Figure 2 illustrates the simplified workflow of the study, outlining the datasets employed and the sequence of analytical procedures applied. Constraint criteria were treated as exclusionary factors and were therefore masked out from the analysis, while suitability criteria were incorporated to identify and prioritize areas appropriate for landfill siting. The integration of these criteria through spatial overlay analysis resulted in the generation of a landfill suitability map, which highlights optimal locations based on environmental, social, and technical considerations.

Data used

Data Used

The primary dataset for this study comprises nine thematic layers representing the key criteria used in the landfill site suitability analysis. These datasets were obtained from multiple sources and prepared as model input layers. Landsat-8 multispectral imagery with a spatial resolution of 30 m was utilized to generate the land-use/land-cover raster through supervised classification, resulting in five major land-use classes.

All spatial layers were either obtained as shapefiles or derived from base-map sources and subsequently clipped to the study area boundary. The datasets included vector and raster formats such as shapefiles, a Digital Elevation Model (DEM), and satellite imagery. Data processing, preparation, and analysis were conducted using ArcGIS (ArcMap version 10.8).

Nine feature classes were developed based on Khartoum State base maps, including agricultural land, geological formations, drainage networks, groundwater resources, the River Nile, soil types, land cover, population density, residential areas, and road networks. Slope information was derived from the DEM, while land-cover data were extracted from remote sensing imagery. These datasets collectively formed the spatial foundation for the multi-criteria suitability assessment.

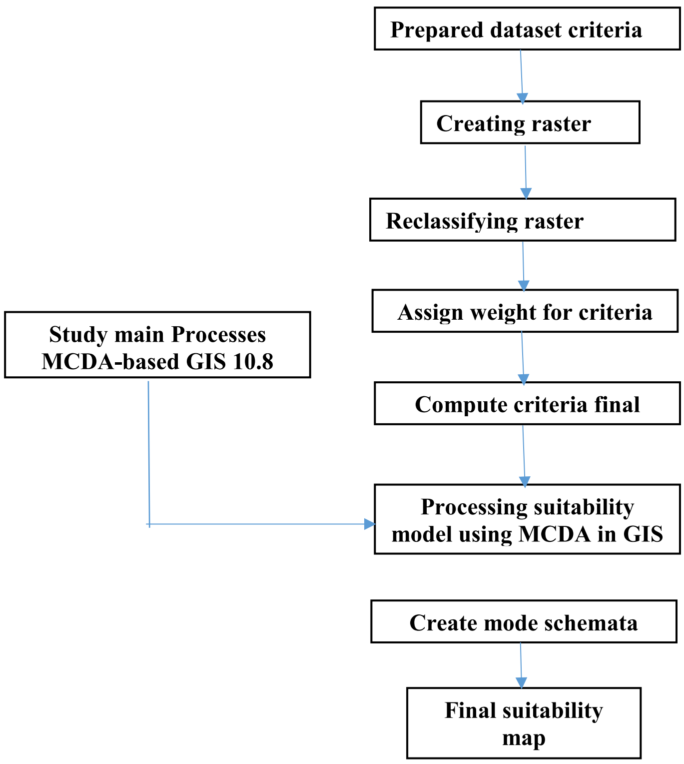

Fig (2): Synoptic chart for methodological workflow

Defining Criteria

The first fundamental step in site selection was the determination of criteria will be used to assess the suitability of land to gain the objectives [16]. Generally, there are two hypothetical views for criteria considerations. The restricted criteria that determine the sensitive environment areas that the landfill location site should only be far away from these areas. Other criteria are suitable for building suitability model for landfill under the control of weighted overlay processing. Residential areas and water bodies were the only criteria that has high weights among the others. The table (1) shows the criteria main rank scales and their weights. The most recommended criteria that are appropriate for modelling the landfill site selection can be explained as follows:

Location

Location is the first factor to be considered in site selection and suitability analysis. Each SWSS (Solid Waste Suitability Site) said to be at a location surrounded by geographic features. Distance is associates with a location when assessing the suitability. Landfill, more or less, should be located at a distance from building, water bodies, and settlements with specific safety considerations.

Buildings (residential areas)

Among the various criteria considered for landfill site selection, proximity to residential areas represents one of the most critical factors from an environmental and public health perspective. Although residential distance alone does not determine landfill suitability, it is assigned a high weight due to its sensitivity and potential impacts on human well-being. Landfills should be located at a sufficient distance from populated areas to minimize risks related to odor, air pollution, noise, and health hazards. In this study, a minimum buffer distance of 10 km from residential zones was applied, with additional consideration given to approved master plans and anticipated future urban expansion to ensure long-term suitability and sustainability. The reasonable distance from buildings is significantly recommended to avoid the building, residents from visual impacts, bad smiles, transferring unwanted material and environmental likely negative events. The distance from landfill is determined the proximity from the residential area that classified into 5 different scale ranges of suitability classes table (1) and Fig (3) that represent reclassified distances.

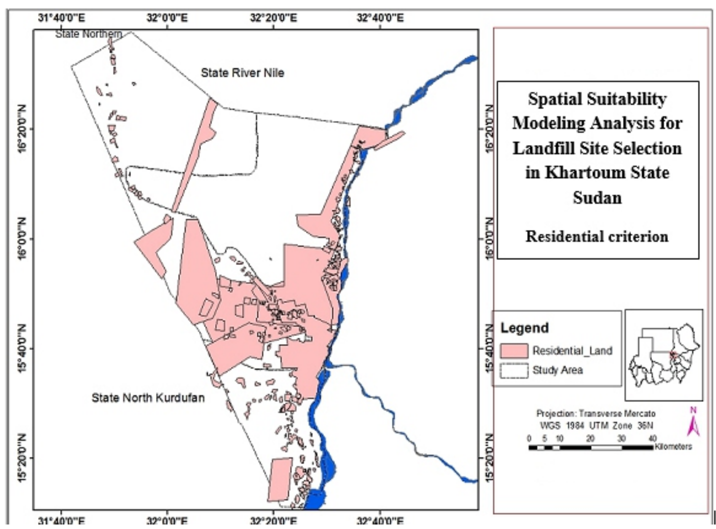

Fig (3): Building areas (residents) criterion feature class

Table (1): Reclassified Criteria Value Important Ranking

Value range	Ranks	Weight	Value range	Ranks	Weight
Building criteria:			**Population density:**		
0 --- 2 km	1		**Low density**	**5**	
2 --- 4 km	2		**Medium density**	3	**9**
4 --- 6 km	3		**High density**	1	
6 --- 8 km	4	**13**	**Soil type criterion:**		
< 20 km	**5**		**Clay soil**	**5**	
Agriculture criteria:			**Clay loam**	4	
0 --- 2 km	1		**Loam**	2	**15**
2 --- 4 km	2		**Sandy soils**	1	
4 --- 6 km	3		**Road's criterion:**		
6 --- 8 km	4	**10**	**1 --- 500 m**	**5**	
< 10 km	**5**		**500 --- 1000 m**	4	
Water bodies criterion:			**1000 --- 1500 m**	3	
0 --- 3 km	1		**1500 ---2000 m**	2	**8**
3 --- 6 km	2		**2000 – 2500 m**	1	
6 --- 9 km	3		**Ground water source:**		
9 --- 12 km	4	**13**	**0 --- 3**	1	
< 15 km	**5**		**3 --- 6**	2	
Slope criterion:			**6 --- 9**	3	
0 --- 5 degree	**5**		**9 --- 12**	4	**8**
5 --- 10	4		**< 15**	**5**	
10 ---15	2		**Geological formation:**		
15 --- 20	3	**17**	**Intrusive rocks**	**5**	
20 --- 25	1		**Sedimentary rocks**	1	**7**
Overall weight	**100**				

Agriculture (farm lands)

The States' land use and landcover classes are represent important criteria to identify suitable site selection for landfill. One of the main landuse to be considered is the agricultural lands, which are the most important sensitive environmental criterion to waste locations, mainly to avoid leachate from landfill. So, landfill should not be established near or at the vicinity of these sensitive lands table (1) and Fig. (4).

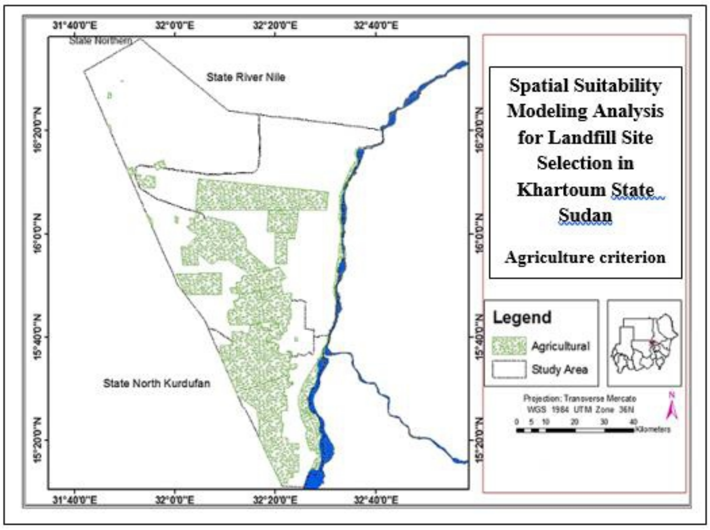

Fig (3): Agricultural areas (predictive lands) criterion feature class

Water bodies (Nile)

Water bodies across the study area varied from the Nile course to include always wades and other wetlands depressions. The landfill site selection far from water bodies, is safer to avoid contamination and water pollution. The far distance from the Nile course, is the better site to keep the waste carried by running water during rainy season or by winds away from the Nile buffering. Based on the distance determined in table (1) and in Fig. (5), the landfill located at a distance not less than 15 Km is very suitable.

Dumping waste directly or indirectly influences the source of surface water. Landfill site should be located beyond the catchment areas. For surfaces water like the river Nile, it should be located 800 m away from the source.

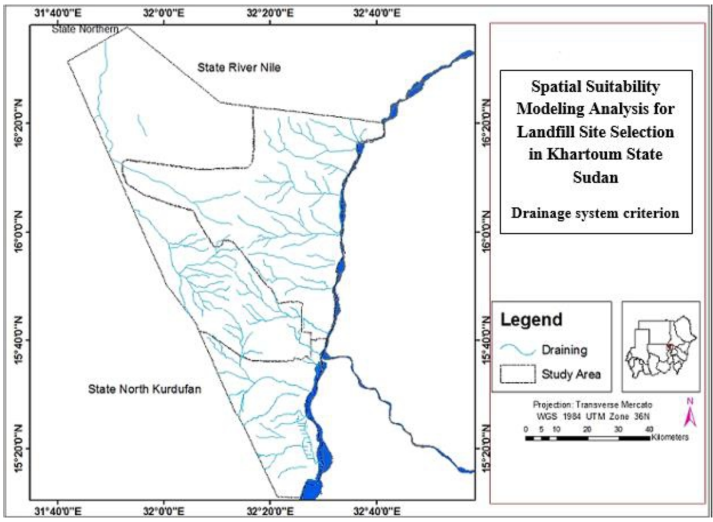

Fig (5): Water bodies (predictive lands) criterion feature class

Geological formations:

To consider the type of geological formation in selecting site for landfill, is crucial as the type of rocks affected the groundwater if they are of high permeable and fractures characteristics and has any geological leakages. The study area geological formations are classified into intrusive and sedimentary rocks. The suitable formation for establishing a landfill is intrusive rocks due to its lesser permeability features for surface water or material to be percolated or leached. So, to avoid joints and fractures are good for landfill likely impacts to affect groundwater quality.

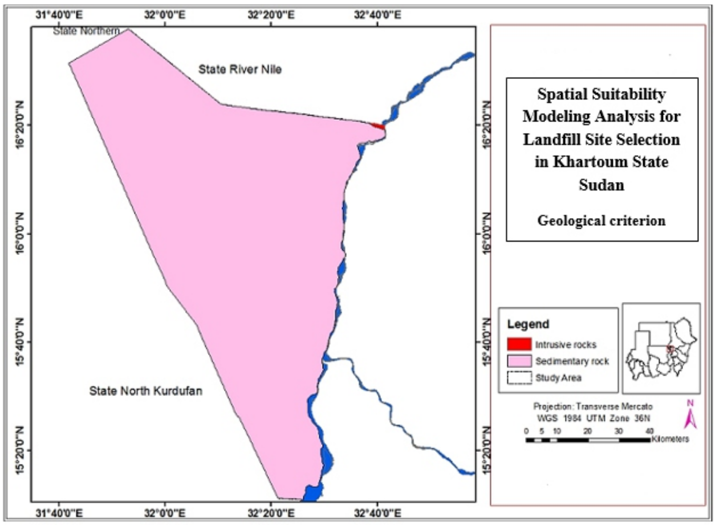

Fig (6): Geological formations criterion feature class

Population density

One of the considerable criteria in building landfill site selection suitability analysis modeling is the population density. Landfills should be avoiding high populated areas for their life quality safety, and healthy environment. The criterion of population density classified into 3 classes; low, medium and high density. Low density area is suitable for landfill site selection, has a score of 5 in the suitability ranking, table (1) and Fig. (4).

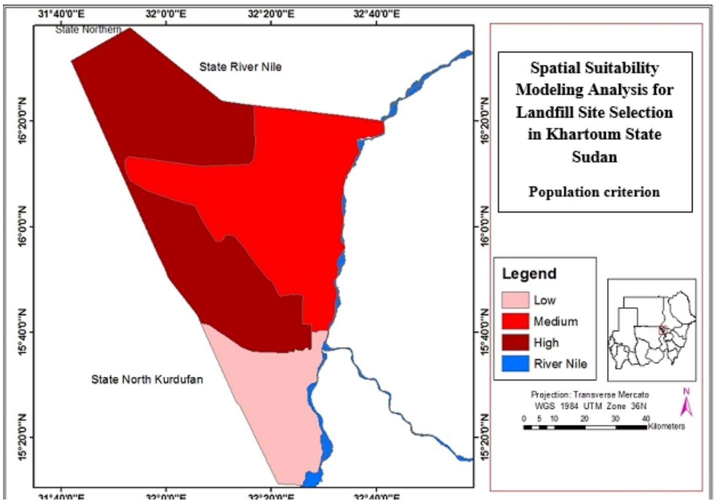

Fig (7): Population density criterion feature class

Ground water sources (wells)

Is one of the very significant factor to be away from the landfill to avoid soil leacgate that affect the quality of the groundwater. The study area ground water sources (wells) are distributed in different patterns as shown in fig. (8).The diastance fron these wels should be away from landfill not less than 50 Km, table (1).

Soli types

There are many types over the study area that not all suitable for landfill site selection. As recommended in literature clay soil is highly suitable for SWLF site selection. The suitability of soil for landfill comes from its soil properties such as permeability and porosity, that based on soil formations and structures. Clay soil low permeability has scale 5 suitability, while clay loam soil comes as second ideal class for landfill site selection. The loam soil is not suitable due to its large texture and high permeability, while sand soil is permanently not suitable for landfill (high porosity and permeability) Table (1) and Fig. (9).

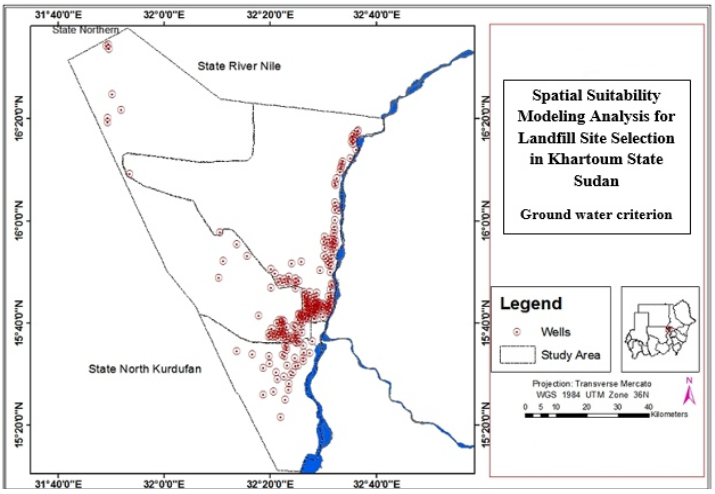

Fig. (8): Ground water sources (wells) criterion feature class

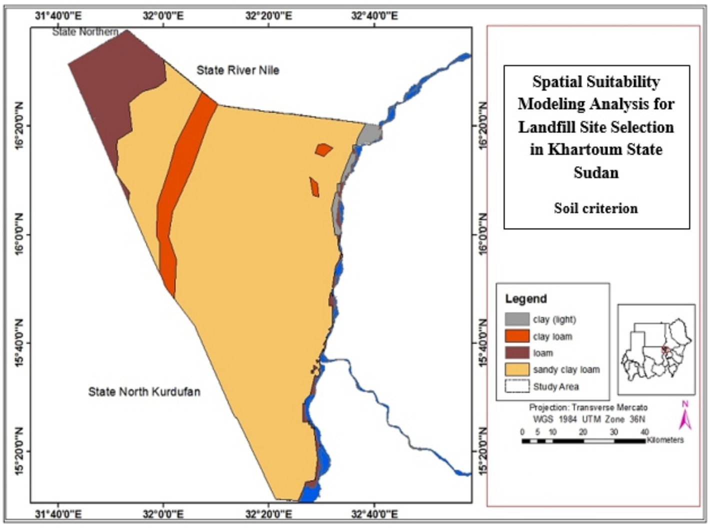

Fig. (9): Soil formations criterion feature class

Roads networks

The relationship between road network and landfill site selection is determined by its value in transporting the waste, so landfill site should be accessible to road networks. Recommended distance from the landfill is 500 meters. This distance as standard, facilitate easy transportation and keep road at the same time away from contamination table (1) and Fig. (10).

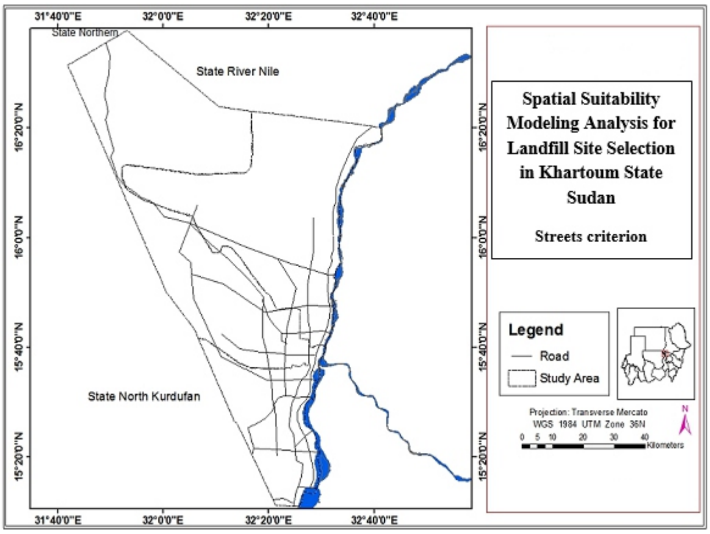

Fig. (10): Streets criterion feature class in Khartoum State

Slope criteria (Digital Elevation Model)

Digital elevation model can be used to extract slope parameters. For this study DEM 100m spatial resolution of Sudan has been used to extract slope criterion. Within the topographical group, slope is categorized as one of the main criteria that affected the potential suitability and site selection of the landfill. For generating slope criteria, DEM data was used as input using surface analysis in GIS environment Fig. (11) which showed slope in degree map reclassified for suitability classes, identifying the flat slope is most suitable than the steep slope. The scale ranged of the slope suitability was classified into 5 classes based on the suitability standard in Table (1). The most suitable class is (C1) that ranges from 0 to 5 degree centigrade, based on the fact that controlling of inflowing water is a critical factor in the locating of such landfills.

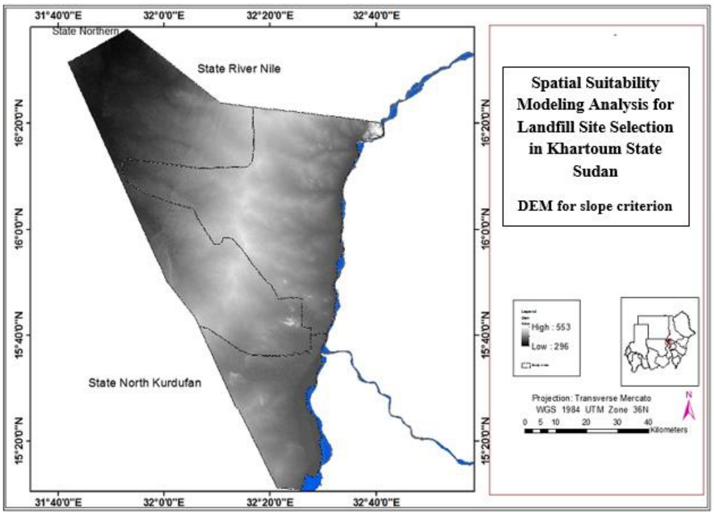

Fig (11): DEM-based data for slope creation feature class in Khartoum State

Methods of Analysis

In many research studies, landfill site selection is recognized as a complex task because it involves multiple interrelated criteria, each with a different level of importance. To address this complexity, suitability analysis based on Geographic Information Systems (GIS) integrated with Spatial Multi-Criteria Decision Analysis (MCDA) has been widely recommended for site selection assessments. MCDA provides a structured framework that enables decision-makers to evaluate and integrate diverse environmental, social, and technical factors systematically. As illustrated in Fig. (1), the methodological workflow adopted in this study applies a multi-criteria evaluation approach to identify suitable landfill locations. Consistent with recommendations in the literature, landfill suitability is treated as a function of the combined influence of multiple criteria, each assigned a score according to its relative importance. The selected criteria were weighted and ranked on a suitability scale ranging from 1 (least suitable) to 5 (most suitable), based on predefined weight percentages. This process was implemented within the GIS Model Builder environment. The resulting suitability classification comprises five classes, where Class 5 represents the highest suitability for landfill development, and Class 1 indicates very low suitability, as summarized in Table (1).

MCDA

Multi-Criteria Decision Analysis (MCDA) methods support decision-makers in identifying optimal solutions or alternatives when undertaking planning activities or making investment decisions within a specific area. The systematically evaluating multiple criteria with varying levels of importance, MCDA enhances the transparency, consistency, and effectiveness of the decision-making process [8]. This refers to Multi-criteria Decision-Making Analysis that many data is created as layers (criteria) are weighted differently as their importance for landfill site selection. All multi-criteria are integrated to conclude the final map that categorizes the range of suitability such as high suitable, suitable, moderate, and low suitable and very low suitable. So, it is a process of preparing appropriate recommended criteria for identifying of new solid waste landfill sites.

Weightage Overlay

Weighted overlay analysis is a widely used spatial modeling technique that generates a composite suitability map by integrating the spatial characteristics and attribute information of multiple thematic layers within a GIS environment. This approach enables the systematic combination of diverse criteria according to their assigned weights, supporting informed spatial decision-making [15]. An important function of multi-criteria is combing several datasets of the modeling using weighted overlay tool. Multi-criteria data set prepared from different data sources are the data inputs for building the suitability model. There are 8 criteria (layers) were weighted to create an appropriate scientific site for landfill. Criteria weighted were identified based on their degree of influence of the variable weighting overlay analysis. Overlay analysis indicated that all layers (criteria) are to be combined and differentiated by their weights, which governed concluding suitable map table (1).

Results and Discussions

Suitability modeling for landfill location

In advanced spatial analysis, the integration of spatial modeling and GIS-MCDA is highly recommended. Landfill site selection is one of the GIS-based utilities that can be realized via suitability modeling analysis. A spatial suitability model for landfill site selection was developed using ArcGIS 10.8. An environmental, social, and infrastructural criteria were analyzed using tools such as Euclidean distance, reclassification, and weighted overlay. Multi-Criteria Decision Analysis (MCDA) was applied to nine thematic layers, each ranked on a suitability scale from 1 (least suitable) to 5 (most suitable). The weighted overlay method integrated all criteria based on their relative importance, resulting in a final suitability map identifying optimal locations for landfill development (Fig. 13).

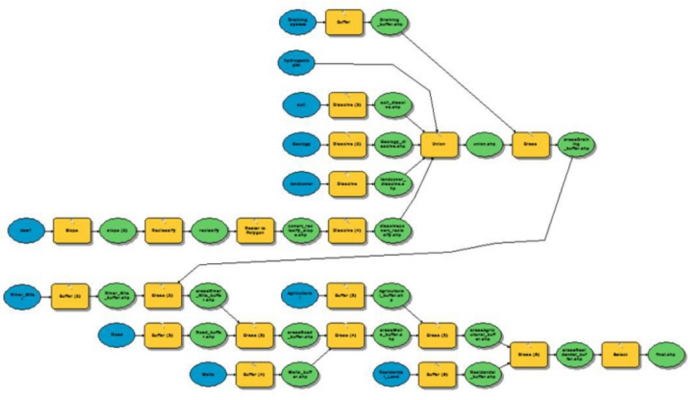

Fig. (13): Model builder using Weight Overlay

Final landfill suitability Analysis:

This the end phase of the sequential spatial modeling processes that showed the potential MCDA method in finding an appropriate landfill site selection. In integrating and combining all reclassified layers, we get by a map that identified the various classes of suitability, which classified into three classes (high, medium and low suitable) for constructing landfill stations. Weights defined for the landfill modeling suitability are 8, 13, 10, 13, 8, 7, 17, 15, 9, for the roads, buildings, agricultural lands, groundwater sources, geological formation, slope, soils, and population density respectively. The final map gives a red color that assigned the very high suitable zones to establish landfill for solid waste Fig. (14).

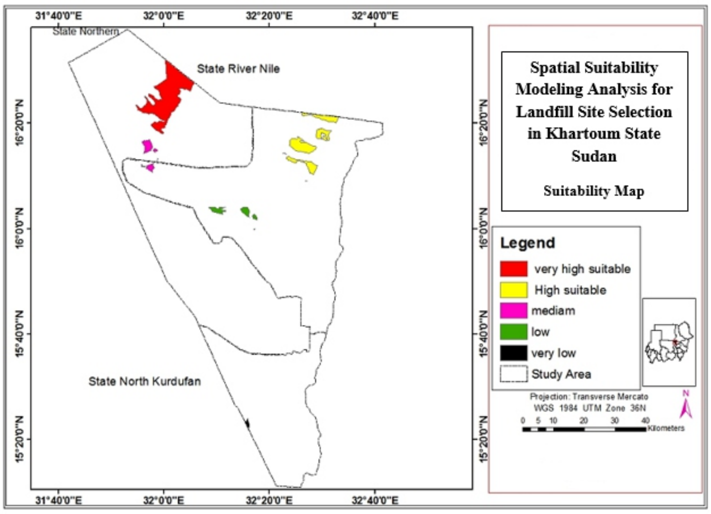

Fig (14): Final Suitability Map

Analysis and Discussion

In contemporary and modern urban environment, the landfill utility becomes one of the crucial issues for municipalities. Scientific approaches for both data preparation (criteria) and analytical tools are help to select an optimal site selection for landfill. Without any debate, location analysis characterizes the suitability modeling analysis and guiding all the processes to conclude the final appropriate site selection. Considering all criteria used, suitability analysis to each of them was showed their significances to landfill site selection. Urban roads networks are important for facilitating solid waste transportation services. When location to landfill is considered, the solid waste to be transported easily is one of the solid waste management successful parameters. The distance proposed is idealized the standard to serve solid waste to land fill. From the final suitability map, the class one (very high suitability) areas need to be planned by new road construction to connect inter-urban areas with landfill suitable location. The suitability analysis to buildings (residents), the distance from the landfill classified onto a common scale (1 to 5). The optimal is that, the far away the residential areas to landfill locations, the better for safer and healthier societies. Residential areas surrounding landfill are highly exposed to contamination or even pollution that has adverse impacts. As far as suitability to agricultural lands (farms) is concerned, the relationship between the locations of landfill and existing farmland in the State was realized the safer distance that used and recognized in the suitability map. On the other hand, the relationship between water bodies (Nile) in this study with the landfills location as identified by the scale used and weight assigned, showed its optimality for far away from the Nile, which is safer for water to be polluted.

Suitability analysis to groundwater sources (wells) also indicated by the Euclidian distance for the classified wells layer. The suitable class depicted in the final suitability amp, showed that there is no wells distributed within the buffer of the selected assigned distance and weight used. To associate land slope of the suitable areas based on the values represents and having the layer's weight and scores ranking based on their importance, the criteria satisfied its assigned condition, which is relatively as flat landscape. The soil types overlay with landfill classified final map indicated that the clay and loamy clay soils characterized the suitable area modelled for establishing landfills. Again, the relationship between landfill location and population density is analyzed showing that low population density areas have 5 score to be suitable for landfill location. From the final map, the high suitable class areas satisfied this condition as the area had less population density. Finally, geological formations (rocks) are highly affected the locations of the landfill. For this study, the layer of geological formations classified into two classes, the optimal for landfill that follow the standard of the score ranking and weight, is the intrusive rocks which characterized the area weighted for suitable site selection.

Conclusions

This study demonstrated the effectiveness of a GIS-based Multi-Criteria Decision Analysis (MCDA) framework for identifying optimal landfill sites in the urbanized areas of Khartoum State. The approach integrated spatial overlay analysis with multiple environmental and anthropogenic criteria within a GIS modeling environment. The factors were selected based on relevant literature as well as local institutional and planning guidelines. The resulting suitability map classified the study area into five levels of suitability. Areas identified as highly suitable represent optimal locations for landfill development, where the weighted combination of all criteria meets environmental, social, and technical requirements. The proposed methodology provides a systematic and replicable decision-support tool that can assist planners and policymakers in sustainable solid waste management and future landfill planning.

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