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Comprehensive Multi-Criteria Evaluation for Landfill Site Selection in Faisalabad, Pakistan

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Introduction/Importance of Study: Solid waste management (SWM) has become a critical issue in urban planning due to population growth and urban migration, particularly in developing countries. In Pakistan, there are no standardized regulations for landfill site selection. Faisalabad, often referred to as the "Manchester of Pakistan" due to its industrial base and growing population, faces significant challenges in this regard. Identifying a suitable landfill site is essential to minimize health and environmental risks and ensure the long-term sustainability of both urban and peri-urban areas.

Novelty Statement: This study aims to propose an optimized landfill site in Faisalabad, combining the Analytical Hierarchy Process (AHP), Multi-Criteria Decision Analysis (MCDA), and Geographic Information Systems (GIS) to guide sustainable solid waste management practices.

Material and Method: The study utilized raster, vector, and attribute data based on eight key criteria: proximity to settlements, groundwater depth, roads, airport, surface water, power stations, railway infrastructure, and population density. Using AHP within the MCDA framework and GIS modeling with weighted overlay operations, we identified potential landfill sites for Faisalabad. Population data was incorporated to validate site suitability.

Results and Discussion: Through geospatial analysis, we identified and prioritized three potential landfill sites. After a population analysis, we recommended Site-1, covering 147 acres, as the most sustainable option for the next 50 years. This site offers a balance between accessibility and environmental safety.

Concluding Remarks: The integration of AHP and GIS under MCDA proved to be an effective method for landfill site selection. These tools can significantly aid decision-makers in achieving environmentally sustainable outcomes. Future research incorporating real-time data and community feedback could enhance site selection and decision-making processes.

Keywords: Landfill Site Selection. Analytical Hierarchy Process. Geographical Information System. Solid Waste Management. Multi Criteria Decision Analysis.

Introduction:

As the global population grows, so does solid waste output, which is expected to reach 3.40 billion metric tons (MT) per year by 2050[1]. Low-income countries (LIC) are projected to experience a more than threefold increase in waste generation by 2050. Asia currently produces one-third of the global waste, with per capita waste generation in countries like India (0.50 kg/day), China (0.43 kg/day), and Pakistan (0.43 kg/day) [2]. While high-income countries (HIC) recycle 51% of their waste, LICs recycle only 16%. Additionally, 93% of garbage in LICs ends up in open dumps, compared to just 2% in HICs. These poor solid waste management (SWM) practices pose significant threats to health, the environment, and livelihoods in LICs. Local municipalities and government bodies in LICs face multiple challenges when implementing new SWM programs [1]. Historically, the lack of proper SWM has made communities vulnerable to health crises, especially during pandemics and natural disasters like hurricanes, earthquakes, and floods [3][4].

Projections indicate that the global population will continue to rise over the next five to six decades, peaking at around 10.3 billion by the mid-2080s, compared to 8.2 billion in 2024[5]. Despite unprecedented economic growth, modern societies are facing a depletion in resource availability, an increase in solid waste generation, and significant environmental pollution [6][7]. Currently, the world produces approximately 2.01 billion tons of municipal solid waste (MSW) annually, with 33% not being properly managed. According to the International Monetary Fund, there is a direct link between a country's GDP per capita and its waste generation rate, with developed nations producing between 1.00 to 2.50 kg of waste per capita per day, and developing countries generating 0.50 to 1.00 kg/capita/day. Tackling the rapid rise in MSW is vital for achieving global sustainability [3][8].

In Pakistan, there are few specific and effective regulations regarding municipal solid waste disposal, aside from some legislation like the Pakistan Environmental Protection Act (PEPA-section-11) and the National Environmental Quality Standards [9]. Faisalabad's population, which stood at 2 million in 1998, had risen to 3.20 million by 2017, making it Pakistan's third-largest city by population [10]. The city’s growing population, urbanization, and industrialization are the primary contributors to the rising amounts of solid waste. Faisalabad generates about 1,600 tons of waste daily, with an annual increase rate of 0.48 kg per capita per day [11]. However, only 1,000 metric tons are collected daily, leaving the rest to be burned alongside roads, which severely impacts the environment and diminishes the city’s visual appeal [11].

The selection of landfill sites is crucial in urban planning as it affects the environment, economy, and public health [12][13][14][15]. A thorough review is needed to choose a sanitary landfill site that complies with regulations while minimizing negative health, socio-economic, and environmental impacts [16][17]. Environmental factors such as groundwater and surface water protection, as well as the preservation of local ecosystems, are crucial considerations [18][19]. Protecting environmentally sensitive areas is essential for preserving water, biodiversity, soil, and other natural resources. Social criteria focus on public health by ensuring dump sites are located far from residential areas, while economic factors emphasize minimizing transportation costs from collection points to the landfill [20][21][17][22][23][24][25].

A wide range of social, economic, and environmental factors must be considered when selecting an optimal landfill site [17]. This research incorporates all relevant parameters to identify an ideal landfill site for solid waste management. The goal is to propose a site that will remain effective for the next 50 years by using Geographic Information Systems (GIS) and the Analytical Hierarchy Process (AHP) within a Multi-Criteria Decision Analysis (MCDA) framework. Given the rapid pace of urbanization and population growth, long-term planning is essential to address this pressing issue.

Objectives:

- To identify and propose an optimal landfill site for solid waste management (SWM) using a geospatial site selection model.
- To evaluate the proposed landfill site's capacity and suitability to meet SWM needs for the next 50 years.

Study Area:

The research focuses on District Faisalabad (31.451175, 73.100007). Faisalabad, formerly known as Lyallpur until 1979, is Pakistan's third-largest city, with a population of 3.20 million [10]. Known for its cotton industry, Faisalabad is experiencing rapid urbanization, driving up demand for landfill sites. The city comprises four towns: Jinnah, Madina, Lyallpur, and Iqbal. District Faisalabad is divided into six tehsils: Faisalabad City, Faisalabad Sadar, Samundri, Jaranwala, Tandlianwala, and Chak Jhumra (Figure 1).

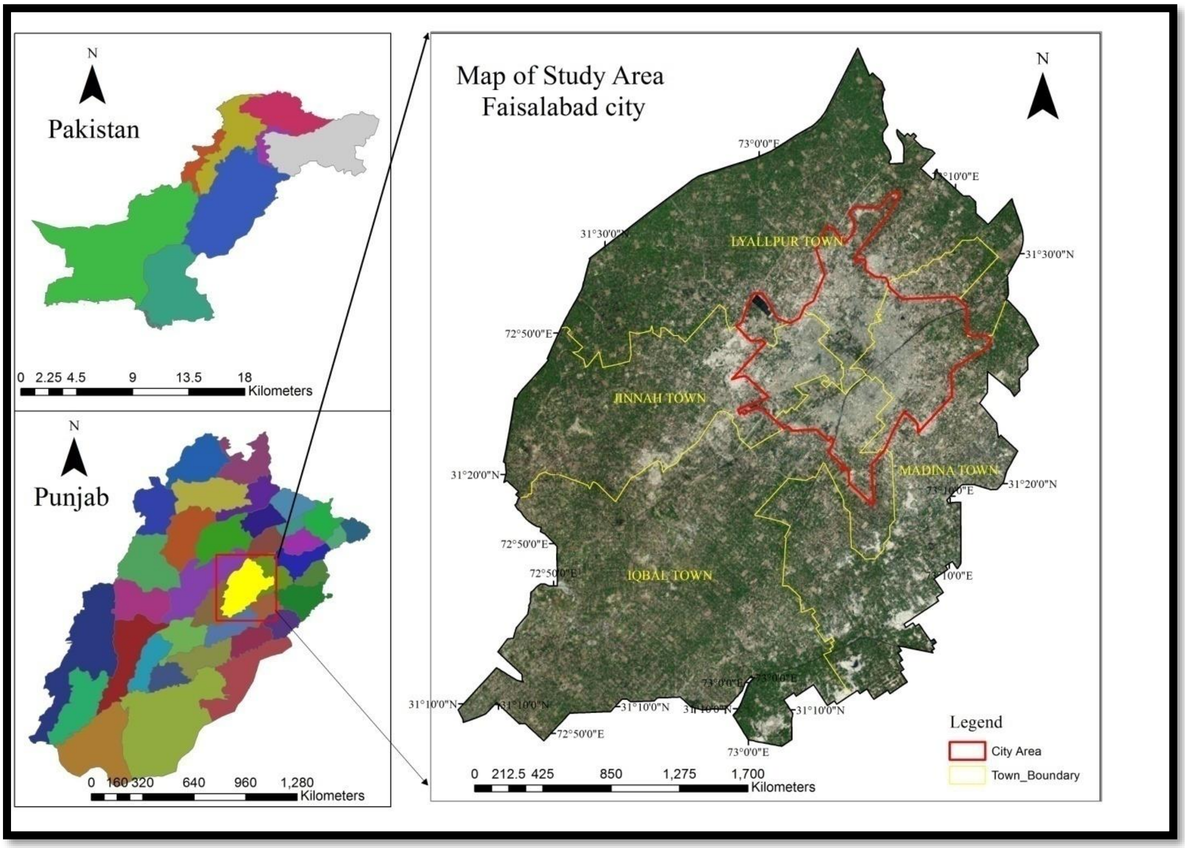

Figure 1: Study Area Map

Data and Methodology:

Dataset:

Finding ideal locations for solid waste disposal requires considering economic, socio-cultural, and environmental factors [26]. For this study, eight criteria were selected: highways, airports, settlements, railway tracks/stations, surface water, power plants, groundwater level, and dynamic population data from the latest census. The demographic data proved valuable in forecasting the population growth over the next 50 years, given Faisalabad's high growth rate [27][10]. Land-use and land-cover (LULC) data was obtained using supervised image classification (SIC). A Landsat-8 image, captured on March 4, 2018, along path 150 and row 38, was processed to extract relevant information (Source: https://earthexplorer.usgs.gov/). After geometric rectification, the image underwent layer stacking and supervised classification using Erdas-Imagine 2014. The classified image was then imported into ArcGIS-10.5 for further analysis, including raster clipping and polygon conversion to estimate proximity to settlements. Figure 2 illustrates the complete methodology flowchart.

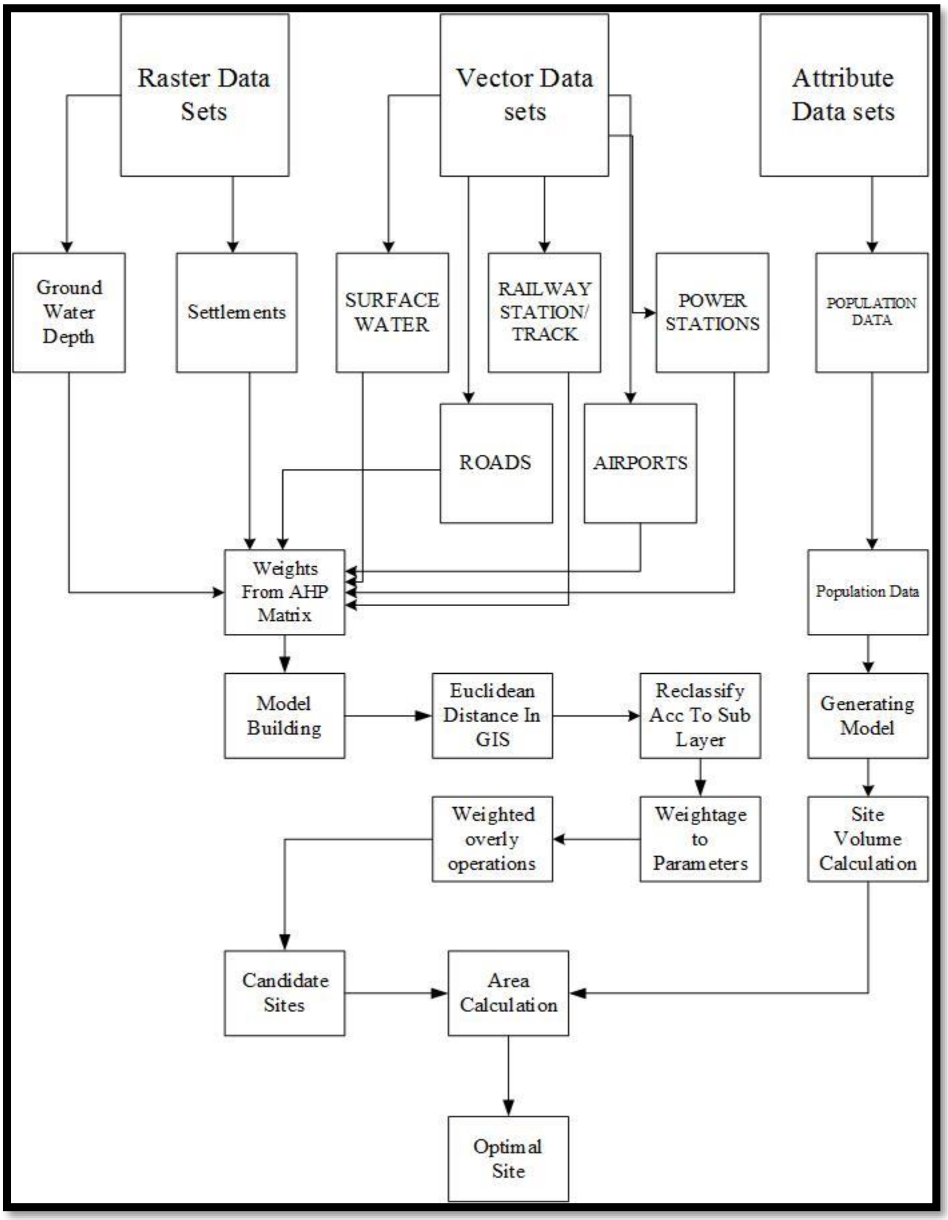

Figure 2: Flowchart of methodological process.

Analytical Hierarchy Process (AHP):

AHP is a powerful tool for decision-making in complex problems, allowing the integration of heterogeneous parameters across various fields [26][28]. It is particularly useful for multi-criteria evaluation (MCE) and can be combined with GIS for suitability analysis [29][30]. As a method within MCDA, AHP helps evaluate and sustain decisions amidst conflicting objectives. A pair-wise comparison matrix was created by organizing parameters into a logical hierarchical structure, reflecting their relative importance to one another. Weights were assigned to each parameter to mathematically link the entire hierarchical process (Table 1). Criteria were scored based on their importance for selecting the optimal landfill site. Distance from settlements was deemed the most critical factor and was ranked highest in the comparison matrix, while groundwater depth and road proximity were assigned lower importance. To ensure the results were reliable, the consistency index (CI) was calculated using Saaty's CI equation, with a consistency ratio required to be below 10% for validity [28][29][31][32]. (Equation 1).

$$CI = (\lambda - n) / (n - 1)$$

$$CI = (7.672746404 - 7) / (7 - 1)$$

$$CI = 0.11212$$

The consistency index (CI) is used to measure the degree of consistency, where *n* represents the total number of criteria, and λ denotes the average consistency. To further verify the consistency of the results, the consistency ratio (CR) is calculated using Equation 2. If the CR value is ≥ 0.10, the results are deemed inconsistent and require revision. However, if the CR value is < 0.10, the results are considered consistent and reliable.

$$CR = CI / RI$$

The consistency ratio (CR) is calculated using the consistency index (CI) and the random index (RI). The standard RI value for calculating CR when *n = 7* is provided in Table 2 [33].

$$CR = CI / RI$$

$$CR = 0.11212 / 1.32$$

$$CR = 0.08$$

The calculated CR value of 0.08, being less than 0.10, indicates that the results are consistent and do not require revision. Therefore, the calculated criterion weights can be confidently integrated into the GIS for further analysis [33][31][32].

Weighted Overly Operations

Weighted overlay is a method used to integrate multiple input layers to find sustainable solutions for emerging issues by standardizing and evaluating conflicting data on a common scale [34][35]. In this study, an evaluation scale from 1 to 9 was employed, where 1 denotes less importance and 9 represents the highest importance or suitability. The weights calculated by AHP were incorporated into GIS for evaluating the optimal landfill site. The total influence values (weights) for all factors, variables, or layers in the weighted overlay must sum to 100%. We created a weighted raster layer by assigning scale weight values to multiple layers based on their relevance. Preference values were distributed across layers and feature classes according to their effects. For instance, a higher scale weight was assigned to a feature class with greater influence. Similarly, a higher scale weight in another layer indicated a more influential feature class. Consequently, the most significant contributing layer received a larger share of the overall weight compared to other layers [36][37][38].

We assigned weights to reclassified criterion sub-layers by multiplying each raster cell value by the percentage influence of the criteria. Various theme layers were analyzed within the ArcGIS environment to achieve the study's objectives [34][35][39]. Table 3 outlines the criteria for selecting the optimal landfill site, specifying suitability limits for factors such as settlement distance, groundwater depth, road distance, airport distance, canal distance, power station distance, and railway track distance. Accessibility and convenience are influenced by settlement distance, while canal distance impacts daily living and health, highlighting the need to mitigate water pollution. The power station distance affects potential site locations near canals. The table provides a summary of the key considerations for landfill site selection [40].

Table 4 highlights key factors such as groundwater depth, environmental issues, and sustainability. It underscores the importance of effective connections between collection points, landfills, airports, canals, and power plants. Additionally, the table emphasizes the need to protect surface water from contamination, crucial for drinking, agriculture, and recreational purposes. Soil fertility and clean surface water are essential for sustainable practices. The table also addresses the impact of distance to railway lines, noting concerns related to odors and noise. It underscores the importance of environmentally friendly practices and technologies [40]. In summary, Table 3 outlines the significance of various elements in selecting the best landfill site, while Table 4 details the criteria for MSW landfill site selection. Previous studies have found the integration of AHP and GIS to be valuable, and this research aims to validate its long-term sustainability. The study is divided into two parts: first, identifying suitable locations for waste disposal, and second, optimizing these sites through population analysis to ensure their sustainability over the next 50 years. The results section provides detailed analyses and outcomes of these efforts.

Table 1: Pair-wise comparison matrix.

AHP Pairwise Comparison of Parameter's										
Criteria listed	**C1**	**C2**	**C3**	**C4**	**C5**	**C6**	**C7**	**AHP**		**Consistency**
								CW	**%Weight- age**	
C1	1	2	3	5	6	7	7	0.355	35.5%	8%
C2	1/2	1	2	4	5	6	6	0.244	24.4%	
C3	1/3	1/2	1	3	3	5	5	0.161	16.1%	
C4	1/5	1/4	1/3	1	2	4	5	0.098	9.8%	
C5	1/6	1/5	1/3	1/2	1	3	4	0.071	7.1%	
C6	1/7	1/6	1/5	1/4	1/3	1	3	0.042	4.2%	
C7	1/7	1/6	1/5	1/5	1/4	1/3	1	0.028	2.8%	
Column Total	2.485714	4.283333	7.066667	13.950	17.58333	26.33333	31.0	1		

C1 Distance-from-settlements, C2 Depth-of-groundwater, C3 Distance-to-roads, C4 Distance-to-airport, C5 Distance-to-canals, C6 Distance-to-Power-Stations and C7 Distance-to-railway-lines/tracks.

Table 2: Random-Index computed for this study [33][40].

Ordered		**1**	**2**	**3**	**4**	**5**	**6**	**7**	**8**	**9**	**10**	**11**	**12**	**13**	**14**	**15**
R. I		0.00	0.00	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.54	1.56	1.57	1.59

Table 3: Suitability range beside Criterion.

Criterion Geo-Layer	Condition	Suitability Distance	Ranking value/logic
C1: Distance to Settlement	Constraint	<1000 m	Restricted
	Low suitable	1000-2000 m	7
	Highly Suitable	>2000	9
C2: Depth of Ground Water	Constraint	<50 ft	Restricted
	Suitable	51-53 ft	7
	Moderately Suitable	55-57 ft	9
	highly Suitable	>57 ft	9
C3: Distance to Roads	Constraint	<500m	Restricted
	Low suitable	500-1000m	7
	Moderately Suitable	1000-2000m	8
	Highly Suitable	>2000 m	9
C4: Distance to Airport	Constraint	<3000 m	Restricted
	Low suitable	3000-6000 m	2
	Moderately suitable	6000-15000 m	7
	Highly Suitable	15000-26000 m	8
	Very highly Suitable	>26000 m	9
C5: Distance to Canal's	Constraint	<500 m	Restricted
	Low suitable	500-1000m	5
	Moderately Suitable	1000-1500 m	7
	Highly Suitable	>1500 m	9
C6: Distance to PowerStation's	Constraint	<500 m	Restricted
	Moderately Suitable	500-1000 m	5
	Highly Suitable	>1000 m	9
C7: Distance to Railway Track	Constraint	<500 m	Restricted
	Moderately Suitable	500-1000 m	4
	Highly Suitable	>1000 m	9

Table 4: Shows the criterion significance for MSW landfill site selection.

C1: Distance to Settlement	Health risk potential. Release of toxic **gases** which can cause air pollution. Aesthetic problems. Property value loss.
C2: Depth of Ground Water	Protection of contamination of GW from Leachate. Futuristic Sustainability of GW.
C3: Distance to Roads	Preservation form odor & aesthetic problems. Connectivity from collection points to landfill site.
C4: Distance to Airport	Due to the presence of organic waste birds can be attracted and can create uncertain condition for airplanes.
C5: Distance to Canal's	To preserve surface water from contamination. Sustainability of soil fertility with clean surface water.
C6: Distance to PowerStation's	Preservation of infrastructure.
C7: Distance to Railway Track	Odor, noise and unpleasant.

Results and Discussion:

Criterion Suitability Maps: To achieve the first objective, we integrated all key criteria using GIS 10.5 in combination with AHP to create a map of optimal solid waste locations, as shown in Figure 3. This map highlights the layers identified as most suitable for establishing optimal landfill sites.

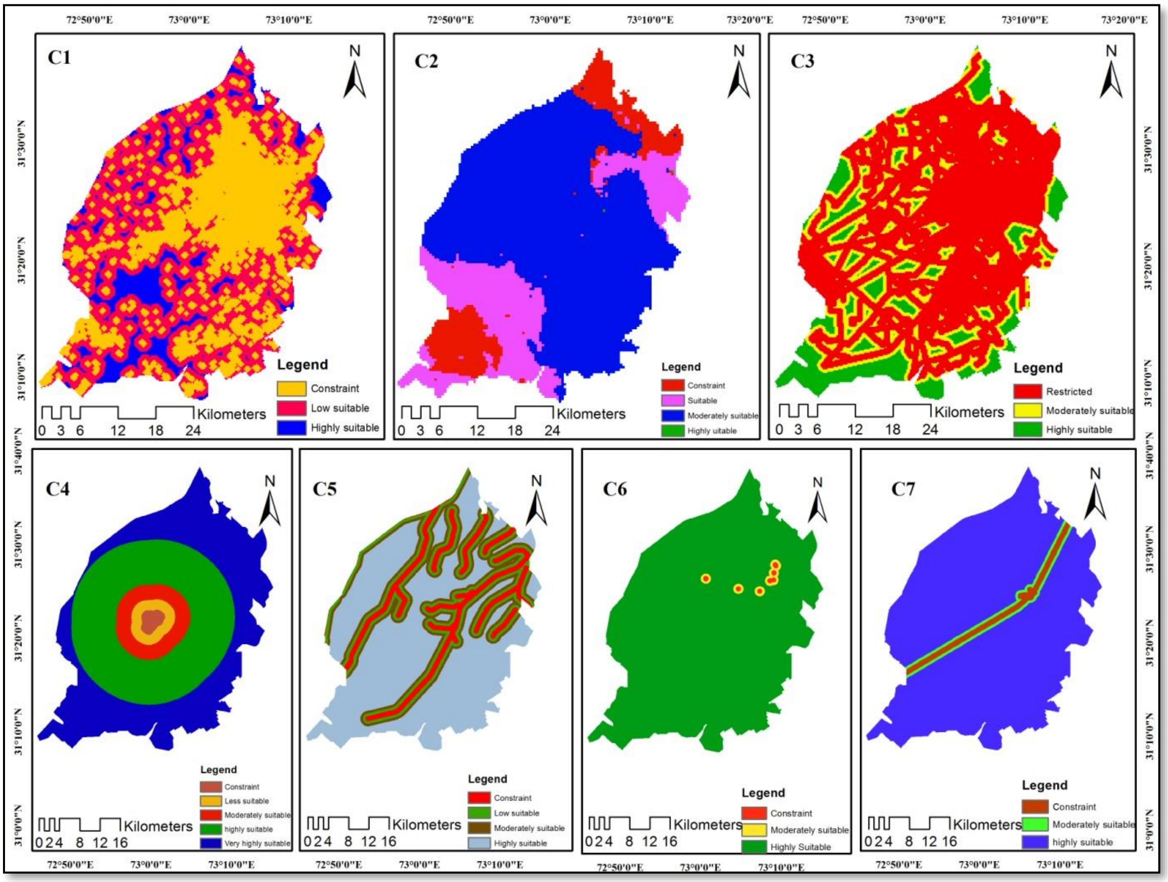

Figure 3: Final Criterion suitability Map (see table 2, 3 and 4 for criteria keys from C1 to C7).

Suitability Analysis:

The study evaluated seven criteria, which were normalized using AHP within the MCDA framework and mapped in GIS to identify the optimal landfill site (the first objective). These criteria include proximity to settlements, groundwater depth, and distances to roads, airports, canals, power stations, and railway tracks. During the AHP weight computation, the consistency ratio (CR) was examined to ensure the results were satisfactory and not contradictory. The weights for the parameters ranged from 0.0 to 1.0, where 0.0 indicates minimal effect and 1.0 denotes significant importance. The weights were 0.355 for distance from settlements (C1), 0.244 for groundwater depth (C2), 0.161 for distance from roads (C3), 0.098 for distance from airports (C4), 0.071 for distance from surface water (C5), 0.042 for distance from power stations (C6), and 0.028 for railway stations/tracks (C7) (Table 3). All criteria were analyzed in the GIS environment to determine site suitability [40].

This analysis identified three potential sites; however, their sustainability over the next 50 years was also assessed as the second objective of the study. For this purpose, a population-based feasibility analysis was conducted to optimize the sites accordingly.

Population data was used for the long-term analysis of this issue, as rapid population growth and urbanization increase pressure on resources. Predicting future population growth is crucial for finding long-term solutions. To estimate future population and growth rate, the following equations were applied [41][42]. The population growth rate was calculated using a specific formula [43]. Recent population data was analyzed to estimate the population in 50 years and determine the landfill volume needed for sustainability. Given that the average household solid waste generation is 1 kg per capita per day, and the compacted waste density in a landfill is 130 kg/m³ [44][45], the required landfill volume for the next 50 years was calculated accordingly.

$$PR = \frac{(Vpresent - Vpast) \times 100}{Vpast} \Big/ N$$

Where,

PR = Population growth rate
V present = Present population
V past = last year population
N= Number of years

$$PR = \frac{(3203846 - 2008861) \times 100}{2008861} \Big/ 19$$

PR=3.13

The estimated population is calculated using the following formula [44][45].

$$Pe = Pf \times (1 + P/100)^{\wedge} n$$

Where,

Pf = most recent population
P = Population growth rate
n = years for which the population is computed.
Pe = projected population after 50 years

$$Pe = 3203846 \times (1 + 3/100)^{\wedge} 50$$

Pe =14,045,359

The estimated population in 50 years is projected to be 14,045,359. With a solid waste generation rate of 1 kg per capita per day, the total waste produced over 50 years is estimated to be 386,692,026.4 kg. Given that the compacted waste density in a landfill is 130 kg/m³ [44][45], the required landfill volume for this amount of waste is 2,974,554 m³. For the landfill model, with a depth of 5 meters, the required area is calculated as 594,910.8 m² (2,974,554 m³ / 5 m). This area is then converted into acres for practical use.

$$1 \text{ Acre} = 4046 m^2$$

$$594910.8 \ m^2 = 147 \text{ Acres.}$$

Hence, the required area for dumping the large quantity of waste is 147 acres. The location and area covered by the optimal landfill site are shown in Figure 4. The proposed sites are near Chak No. 84 and 257 in district Faisalabad. These locations were identified through GIS index modeling (weighted overlay) and optimized to match the calculated site area of 147 acres [40].

This study focuses on selecting landfill sites in Faisalabad, Pakistan. It uses a comprehensive approach that integrates the Analytical Hierarchy Process (AHP) and Geographic Information Systems (GIS) to identify suitable locations for landfill and solid waste management (SWM). The methodology employs eight criteria to ensure the chosen site minimizes health and environmental risks. The use of AHP for prioritizing criteria and GIS for spatial analysis demonstrates a robust decision-making process that considers multiple factors. This approach is efficient for landfill site selection due to its capacity to manage and analyze large data volumes, making it highly effective for site selection research [46][47][48]. Recently, this method has been extensively applied in studies for identifying suitable locations [16][49][50][51][52].

Several researchers in Pakistan have applied this method to identify suitable locations for solid waste disposal [12][53][54][16][55][56]. For instance, [16] employed AHP-GIS and similar variables to this study for landfill site selection, identifying 12 suitable sites. They further validated their findings through ground truthing and least-cost path analysis. In contrast, our study used population analysis to evaluate the future sustainability of the site, ensuring it is viable for 50 years. Several studies have incorporated population growth to assess site suitability, such as [46][57][58], which evaluated landfill size based on population growth, garbage generation, and annual volume.

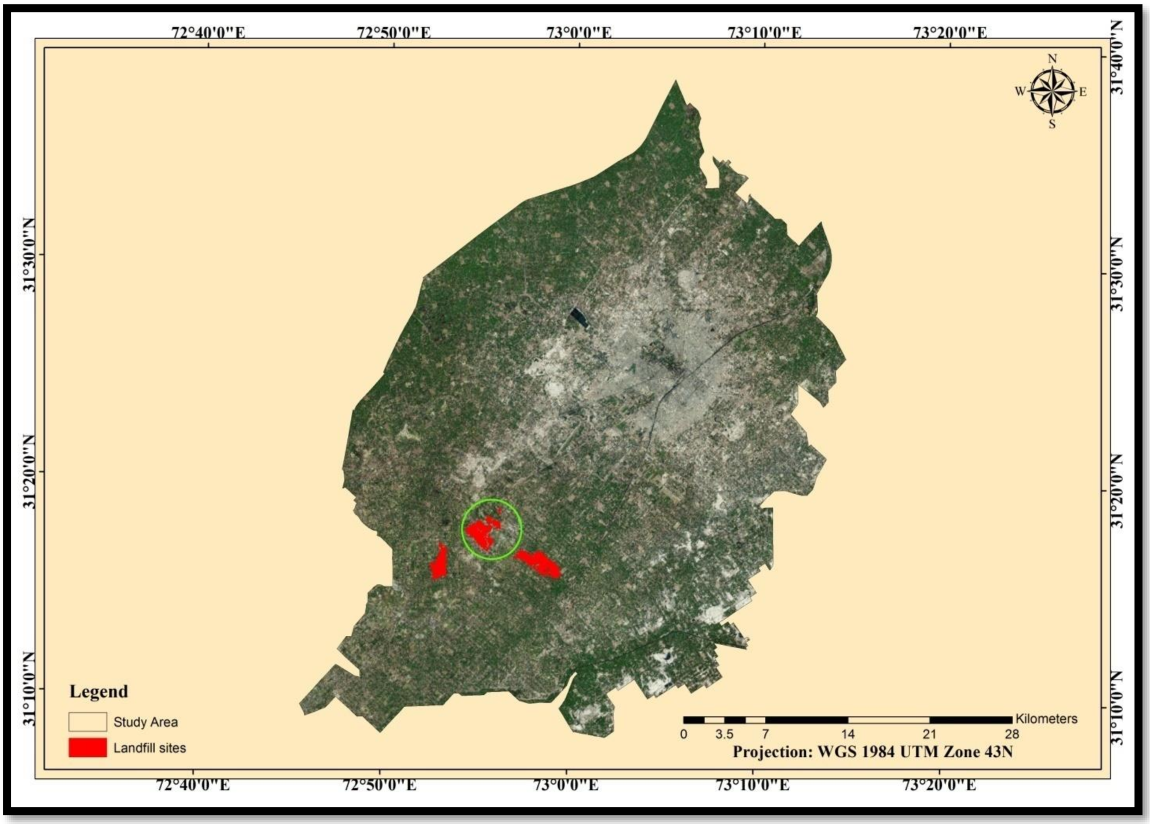

Figure 4: Suitable location for landfill site

According to [53], the situation in Faisalabad is more challenging than in Rawalpindi and Islamabad. With increasing population and urbanization, managing solid waste is a significant task for government bodies. This study proposes prospective landfill sites to mitigate the adverse effects of open garbage dumping on the economy, public health, and the environment in Faisalabad. The site selection process was particularly critical due to the city's dense development [11][59][60][61].

Prioritizing criteria such as distance from settlements and groundwater depth reflects a thorough understanding of the potential impacts of landfill sites on communities and natural resources. This approach aligns with [16][62], which emphasized the need to protect groundwater from contamination. The proposed site, named Site 1, appears to be a well-considered choice based on detailed analysis. While the study is comprehensive, integrating real-time data and community feedback, as suggested by various researchers, could further refine the site selection process [63][64]. Engaging local communities and stakeholders could provide valuable insights and foster public acceptance, as advocated by [65], who highlighted the importance of including public opinion in waste management decisions. Thus, this research provides a robust framework for landfill site selection, potentially serving as a model for other cities with similar challenges. The combination of AHP and GIS, along with consideration of dynamic population data, sets a precedent for future studies in solid waste management. The study underscores the importance of advanced landfill site selection methods to ensure public health and environmental sustainability amidst rapid urbanization and population growth.

Conclusion:

In conclusion, this study offers a comprehensive methodology for selecting a sustainable landfill site, integrating environmental protection with social demands. By employing advanced geospatial techniques and multi-criteria decision-making processes, the research provides a replicable model for other rapidly urbanizing areas facing similar solid waste management challenges. The selection of Site-1 as the optimal landfill for the next 50 years highlights the importance of proactive planning in municipal waste management. Future research should build upon this work by incorporating dynamic environmental and demographic changes to continually enhance landfill site selection procedures, ensuring long-term sustainability and protection of public health.

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