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Municipal Solid Waste Landfill Site Selection Based on Fuzzy-AHP and Geoinformation Techniques in Asir Region Saudi Arabia

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Abstract: One of the main issues with solid waste management is finding appropriate sites for landfill. Non-scientific and inappropriate disposal practices have a negative impact on the environment which affects the quality of life. The study provides an integrated framework with a focus on structuring the decision-making process for the landfill suitability site map. This could be determined by the use of proper data collection, criterion weighting and normalization. In order to understand the procedures that affect the suitability of landfill sites, the integrated GIS-based fuzzy-AHP-MCDA method was implemented to appropriate landfill site for Abha-Khamis-Mushyet located in Aseer region Following the extensive literature review and expert opinion, 10 themes were selected for this study such as drainage density, land use/land cover (LULC), slope, elevation, lineament density, normalized difference vegetation index (NDVI), rainfall, distance from the airport, distance from road, and geology. These themes have been developed through RS (remote sensing) and conventional data. Subsequently, potential landfill sites were identified and divided into five classes: very low suitable (fuzzy value 0.20–0.45), low suitable (0.46–0.55), moderately suitable (0.56–0.65), high suitable (0.66–0.75), and very high suitable (0.76–0.92). According to the statistical analysis, 23.91% and 3.67% of the total area were within a very good and good landfill area, while 38.14% and 22.84% accounted for the moderate and poor suitable zone, respectively. As a quality-based site, the existing two landfill sites were located over a very low suitable and low suitable potential area while one landfill site was located over the high suitable· The spatial variance of high and very high potential landfill site zones found in the north-eastern, east-central and south-eastern parts of the watershed. The sensitivity analysis was performed to determine the efficacy of each parameter and reveals that the effective weights for each theme differ slightly from the theoretical weight assigned to the landfill site suitability zone. This technique and its findings can provide an appropriate guideline to assist hydrogeologists, engineers, regional planners, and decision-makers in selecting an optimal landfill site in the future.

Keywords: suitability analysis; geospatial technique; MCDM; waste management; landfill site potential zone

Citation: Mallick, J. Municipal Solid Waste Landfill Site Selection Based on Fuzzy-AHP and Geoinformation Techniques in Asir Region Saudi Arabia. *Sustainability* **2021**, *13*, 1538. https://doi.org/10.3390/su13031538

Academic Editor: Carlos A. Teixeira

Received: 27 December 2020
Accepted: 28 January 2021
Published: 1 February 2021

1. Introduction

Municipal solid waste (MSW) is generally used to describe as all solid waste produced by domestic, industrial, commercial, institutional, or constructional waste and its substances, i.e., metals, food, plastics, glass, and paper [1–4]. Municipal solid waste management has become a top priority for urban planners, municipal authorities, and decision-makers, growing population, industrialization, and urban sprawling [5]. In developing countries, problems are becoming more serious where the non-scientific method of solid waste management is practiced due to population growth, urbanization, and low human awareness [6,7]. It has become one of the main challenges in urban planning, particularly in developing countries due to increased waste generation and high handling costs [8,9]. The rapid increase in MSW from urban sprawl causes severe water, air, and environmental pollution, particularly in urban areas [10]. Not only does the pace of urbanization and population growth generate large volumes of solid waste, but it also leads to the improper disposal of such solid waste, which is now a major environmental problem facing people [11,12].

Solid waste management includes generation, collection, transport, and disposal [13]. "Solid waste disposal methods include open dumping, sanitary filling, composting, incineration, grinding and sewage discharge, compaction, hog feeding, milling, reduction, and anaerobic digestion" [14]. Waste disposal plays an important role in environmental and public health impacts [15]. Non-scientific and inappropriate disposal practices have harmful effects on surface water, groundwater, soil, and air, which also have a significant impact on the quality of life [16]. Various waste management techniques are available, such as reduction, reuse, recycling, composting, energy recovery, disposal, or landfill [17]. The landfill is the worst strategy or the lowest waste management hierarchy, which has an environmental impact [11,12,18]. Inappropriate landfilling also poses health risks. Various literature indicates possible health impacts on people living near landfill sites and incinerators [19,20]. Any dumping or disposal practices related to reproductive complications and other adverse results such as low birth weight, congenital malformations, multiple births, respiratory disorders, the abnormal sex ratio of newborn, gastrointestinal symptoms, skin infection, and even cancer [21–24].

In the last few decades, Saudi Arabia's urban and semi-urban population has increases dramatically [25]. Saudi Arabia generates more than 15.3 million tons of municipal solid waste per year with a population of 30.8 million [26]. Waste generated per person per day is estimated to be between 1.5 and 1.8 kg per person per day [27]. Approximately 75% of the population is concentrated in urban areas, and government action is needed to strengthen the recycling and waste management scenario [28]. MSW generation has increased due to lifestyle changes and increases in per capita income, therefore proper disposal and management are needed [29]. In developing countries, MSW's collection is difficult due to lack of funding, inadequate facilities, the absence of community outreach and awareness-raising has become a major concern for government and NGOs. Waste is disposed of in an unsuitable location that affects the climate, water supply, and the esthetics of the environment. Several approaches have been proposed to handle MSW, including recycling, source reduction, and incineration, but MSW's most conventional and widespread activity is landfill disposal [29].

The Saudi administration is aware of the crucial demand for a solution to waste management and has invested millions in solving the problem [28]. In 2017, the total national budget of SR 54 billion was allocated to municipal services, including the waste disposal and drainage system [26]. The Saudi administration is working closely to strengthen recycling and waste management activities. The Saudi administration has recently approved new directives providing for an integrated municipal waste management system [26]. The Ministry of Municipal and Rural Affairs (MOMRA) will administer the duties and responsibility of solid waste management policy. On the other hand, more serious efforts are needed in the Kingdom to improve the waste management scenario [26]. Modern waste management strategies, including materials recovery facility, energy waste systems, and recycling facilities, can be implemented methodically and can also greatly enhance the waste management scenario and promote local employment opportunities [26].

Selection of landfill sites is significant, as it has a negative impact on the regional and micro-climate [30,31]. Random and non-scientific selection of landfill sites may have a negative impact on the climate, people and surrounding aquatic resources, including groundwater [32]. It has been argued that knowledge regarding hydrology, land use/land cover, geology, and landfill site understanding is most relevant before selecting suitable landfill sites [33].

2. Literature Review

Many researchers around the world have studied municipal solid waste disposal problems in waste management using MCDM alone or in combination with other methods.

In the analysis of the location of the waste facility, many studies have applied multi-objective methods [34–36]. In order to minimize public and ecosystem exposure, utility location models have also been widely used for the location of MSW landfill sites. The use of GIS and remote sensing for the identification of the landfill site is more cost-effective and efficient than conventional methods [37]. A number of GIS-based approaches have also been proposed for the effective selection of landfill sites [38,39]. Siddiqui et al. [40] adopted the GIS coupled with Analytical Hierarchy Approach (AHP) to determine the viability of the site for the landfill. Some methods for landfill sites integrate Multi-criteria decision analysis (MCDA) with GIS [41–48]. Charnpratheep et al. [49] used the fuzzy set theory coupled with GIS for the assessment of landfill sites in Thailand. The need for the use of MCDM techniques in solid waste management systems was discussed by Cheng et al. [50], as these frameworks could have complex and inconsistent impacts on various stakeholders. Sener et al. [51] have adopted an integrated system of GIS-based MCDM to provide an effective tool for solving the problem of landfill selection; GIS has enabled better data manipulation and presentation, and MCDM has consistently ranked potential landfill sites based on various criteria.

MCDA assists decision-makers rank a set of alternatives by contrasting them with other variables based on how they work with each criterion [37]. MCDM sets a preference-ordered class for several variables. The preferences of decision-makers depend on the relative importance of options according to a number of criteria defined by experts or stakeholders [37]. In the environmental decision-making process, the integration of spatial data using GIS-based MCDM for suitable sites has been considered to be a significant analytic method for formulating and solving the spatial problems of multi-decision objectives [52]. A multi-criteria decision analysis (MCDA) and weighted overlay analysis were used for the suitable landfill site using GIS environment [53]. Various thematic layers for information such as drainage patterns, soil type, topography, geology, structure, and network, have been generated and integrated to develop the best landfill sites. Various experts used these different methods to select appropriate landfill sites [54]. Currently, the fuzzy set has been commonly used in conjunction with the MCDM approach to addressing vagueness in the selection of landfill sites [45,55]. Yesilnacar et al. [56] adopted geospatial techniques for the identification of MSW-landfill sites in Şanliurfa, Turkey. The study shows that the integration of GIS with MCDA is a feasible choice to traditional methods. In the Ayaim et al. [57] analysis, the GIS and MCDM approaches were used to assess the suitability of MSW landfills sites in Ga South, Ghana, and the AHP approach was used to weight and incorporate criteria. In order to evaluate the suitable site for MSW landfills, Karimi et al. [58] adopted geospatial techniques that take into account environmental, geographical and economic constraints in Regina, Canada. They concluded that the best locations for landfill sites are far from water sources, protected areas, populated areas, and road-accessible areas.

One of the GIS-MCDA techniques used in many decision-making processes is the Analytical Hierarchy Approach (AHP) [59]. Despite the success of AHP, the approach is often criticized for failing to address sufficiently the inherent uncertainties and inaccuracies linked with mapping decision maker's perceptions of crisp numbers [60]. The pairwise matrix of the AHP is based on expert choice and therefore, when used to make comparative decisions, introduces a degree of subjectivity. Any incorrect observation by the expert of the roles of the criteria will adversely affect the weighting of the individual criteria [61,62]. AHP can be combined with fuzzy logic approaches to address ambiguity and provide a basis for an additional study that relies on the merits of fuzzy membership.

In the context of the MCDA, fuzzy sets were used to standardize criterion maps to assigning to each entity the degree of membership or non-membership of each criterion [63]. The integration of the AHP with a fuzzy set theory allows for more flexibility in the analysis of results and subsequent decisions. A fuzzy-AHP (F-AHP) maintains several of the benefits that traditional AHPs have, in particularly the relative simplicity in which various quantitative and qualitative data parameters and combinations are managed. As per

AHP, it offers a pair-wise comparison and promotes decomposition, hierarchical structure, minimizes inconsistency, and produces priority vectors. Eventually, the Fuzzy Analytical Hierarchy Approach (FAHP) is capable of representing human observation in that it uses approximate knowledge and ambiguity to make decisions [64]. These features provide a rational basis for the use of the FAHP to help make complex decisions in geo-environmental issues [65]. In relation to a specific attribute of interest, Fuzzy set theory uses a membership function that characterizes the degree of membership value. In general, the interesting attribute is computed over discrete intervals and the membership function can be shown as a table for the classification of the map to the membership values [66]. Fuzzy logic is easy to perceive and incorporate and has been successfully incorporated into GIS-MCDA. In a wide range of research areas, GIS-based MCDA can be performed along with fuzzy set theory for imprecise modeling purposes [41,67], primarily for the selection of landfill sites mapping purposes [48,68]. Since the suitable landfill sites mapping method deals with a number of parameters it can be presumed that incorporation of the fuzzy set theory with the MCDA, and in particular with an F-AHP, would contribute to improving the reliability of the suitable landfill sites maps due to the versatility of the fuzzy membership functions.

Table 1 shows the literature review of the MSW landfill and management related studies: an international scenario. This study, however, complicates the selection of landfill sites, which is not easy to use. Thus, in the current research, the fuzzy MCDM method, i.e., the Fuzzy Analytical Hierarchy Process (FAHP), was carried out for the suitability analysis of the selection of municipal waste landfill sites, since it provides an effective language for the management of imprecise parameters by evaluating quantitative and qualitative factors.

MSW generation in the Abha-Khamis Mushyet metropolis has increased dramatically in recent years due to population growth and changing patterns of consumption. While waste management programs emphasize minimizing waste generation and optimizing recycling and reuse, landfilling is a common way of managing MSW in developing countries such as Saudi Arabia. MSW landfill and disposal is often seen as the easiest and cheapest waste management choice in Saudi Arabia, but many problems linked to a lack of policies, strict legislation and strategies for solid waste can be attributed to poor waste management within Saudi Arabia [29]. Although local municipalities and some private companies manage the collection of solid waste, existing waste management is important within the cities. This situation is almost the same in all cities in Saudi Arabia. In Saudi Arabia's urban planning process, the location of proper MSW landfill sites is very crucial. The key objective of deciding the best location for landfill sites is to reduce negative environmental, ecological, and economic impact [41]. Abha-Khamis Mushyet Metropolis is the main twin city in the south-western part of the Aseer Province of Saudi Arabia. Its population has risen from 608,436 in 1992 to 888,391 in 2010 and 1,026,040 in 2019 [https://www.stats.gov.sa/]. This may be due to the fact that the municipal waste recycling system is not established in proportion to the increase in waste generated, and the majority of MSW is buried or disposed of. There are two landfills around Abha-Khamis Mushyet, one of which is saturated and the other in an unsuitable location and an unsanitary state. The semi-arid condition in Abha-Khamis Mushyet is a leading cause of public health issues and health risks. Consequently, taking into account the amount of waste generation and the lack of land disposal, it is of concern to find a suitable location for municipal landfill sites, taking into account environmental and health concerns.

The aim of this study is therefore to assess the suitable municipal landfill site based on a GIS AHP-Fuzzy hybrid. A questionnaire-based survey was designed to extract expert knowledge and obtain weighting factors for each parameter using the AHP method. The framework was designed to integrate socio-economic and environmental criteria in order to simplify the high-precision method for selecting landfill sites in the GIS platform and to be easily used by waste management authorities in developing countries, including Saudi Arabia. The results of the study may be used in the decision-making process for choosing appropriate landfill sites. This will minimize costs and time and contribute to better management. The remainder of the paper is structured as follows. The following section offers a brief Study area description and solid waste generation. The fourth section deals with Materials and Methods. The fifth section presents the result. The sixth and seventh about discussion and conclusion are presented to provide a discussion of the procedures that affect the suitability of landfill sites i.e., the integrated GIS-based fuzzy-AHP-MCDA method was implemented to appropriate landfill site areas. The suggested method determines that a high-reliability landfill site potential map can be generated by the fuzzy set theory coupled with GIS-based AHP-MCDA.

Table 1. Literature review of studies related to municipal solid waste (MSW) landfill and management: an international scenario.

References	Method	Criteria/Factors	Objectives	Study Area
Guler and Yomralioglu [69]	GIS and AHP	"Social, economic and environmental criteria"	"Ranking land suitability for landfill sites"	Istanbul, Turkey
Leao et al. [70]	GIS based MCDM	"General criteria and complicated parameters such as population growth, location of expanding populations"	"Assessing the lifespan of an existing landfill and the optimal location for siting of a landfill site"	Porto Alegre, Brazil
Melo et al. [71]	"GIS incorporated Fuzzy AHP"	"Social, economic and environmental criteria"	"Ranking and rating of landfill sites"	Brazil
Javaheri et al. [72]	"Multi-criteria evaluation methods combined with GIS"	"Land use, socio-economy and hydrogeology"	"Selection of Landfill site"	Giroft city, Iran
Sumathi et al. [53]	GIS, MCDA, overlay function, AHP	"Social, economic and environmental criteria"	"Selection of Landfill site"	Pondicherry, India
Babalola and Busu [73]	ANP combination of GIS and MCDM	"Social, economic and environmental criteria"	"Selection of Landfill site"	Damaturu, Nigeria
Şener et al. [74]	GIS and AHP	"Land use, hydrogeology and environmental criteria"	"Disposal site selection"	"Isparta, Basin, Turkey"
Adeofun et al. [75]	GIS and RS techniques	"Land use and hydrogeology"	"Selection of dumpsites Abeokuta, and transport routes"	"Abeokuta, Nigeria"
Ebistu and Minale [76]	GIS, RS techniques and MCDM	"Environmental, social and economic criteria"	"Suitable solid waste dumping sites"	"Bahir Dar Town, Ethiopia"
Mănoiu et al. [77]	Suitability Index based on GIS	"Environmental and legal criteria"	"Suitability for landfill placement"	"Prahova, Romania"
Oyinloye [78]	GIS and RS techniques	"Soil type, LULC, transportation routes and proximity to surface water"	Selection of Landfill site	Ondo State, Nigeria
Son [79]	The hybrid method between Chaotic PSO	"Land use, road network and the total collected waste quantity"	"Optimal solutions from the vehicle routing model of Danang"	Danang, Vietnam
Malakahmad et al. [80]	GIS and RS techniques	"Land use, road network and the total collected waste quantity"	"Solid waste collection Ipoh city, routes optimization"	"Ipoh city Malaysia"
Sule et al. [81]	GPS, GIS, and satellite data	"Social, economic and environmental criteria"	"Solid waste disposal management"	"Niger State, Nigeria"
Davami et al. [82]	GIS and Local Screening Method (LSM)	"Social, economic and environmental criteria"	"Selection of Landfill site"	"Ahvaz City, Iran"
Balasooriya et al. [83]	Semi-quantitative riskassessment based on GIS	"Social, economic and environmental criteria"	"Selection of Landfill site"	"Kandy District, Sri Lanka"
Kharat et al. [84]	Integrated fuzzy MCDM approach	"Social, economic and environmental criteria"	"Selection of Landfill site"	Mumbai, India
Yildirim et al. [85]	GIS and MCDM	"Social, economic and environmental criteria"	"Selection of Landfill site"	Bursa Province, Turkey
Pasalari et al. [68]	fuzzy AHP and GIS	"Social, economic and environmental criteria"	"Selection of Landfill site"	Shiraz city, Iran
AlHumid et al. [28]	fuzzy AHP and PROMETHEE II	"Public service and participation, personnel, physical assets, operational, environmental, sustainability, and financial"	Ranking and rating of landfill sites	QassimRegion, Saudi Arabia
Ali and Ahmed [48]	Fuzzy-AHP and geospatial technique	"Social, economic and environmental criteria"	"Selection of Landfill site"	Kolkata, India

3. Study Area Description and Solid Waste Generation

Abha-Khamis Watershed, south western part of Saudi Arabia has a semi-arid climate with undulating and mountainous terrain. The watershed covers an area of 1773 km^2 (Figure 1). The topography of Aseer is sturdy and has mountain peaks which are almost 2990 m above sea level. The watershed has some of the highest peaks in Jabal Alsouda near Abha. Some small Wadi is formed in the higher mountains due to the high amount of rainfall that the higher mountains receive, but none of the Wadi flow for more than 50 km before turning into the Wadi plains [86]. The south-western coast of Saudi Arabia, described as semi-arid region, is surrounded by mountainous topography, where irregular heavy rainstorms occur throughout the year [87]. Due to wet oceanic currents, the region receives rainfall due to south-western monsoon [86]. High temperatures over the peninsula during the summer have led to the development of tropical continental air, which is part of the low circulation monsoon in the northwest of India [86]. The regions receive the highest amount of rainfall during March to June and even flash floods are observed in the downstream areas [87]. The maximum amount of rainfall is received during April with an annual average of 244 mm. Rainfall is the results of orographic convection over the scarp in the Aseer region, especially during the late summer monsoon season. Rainfall exceeding 200 mm per annum is limited to a 20–30 km wide crest zone.

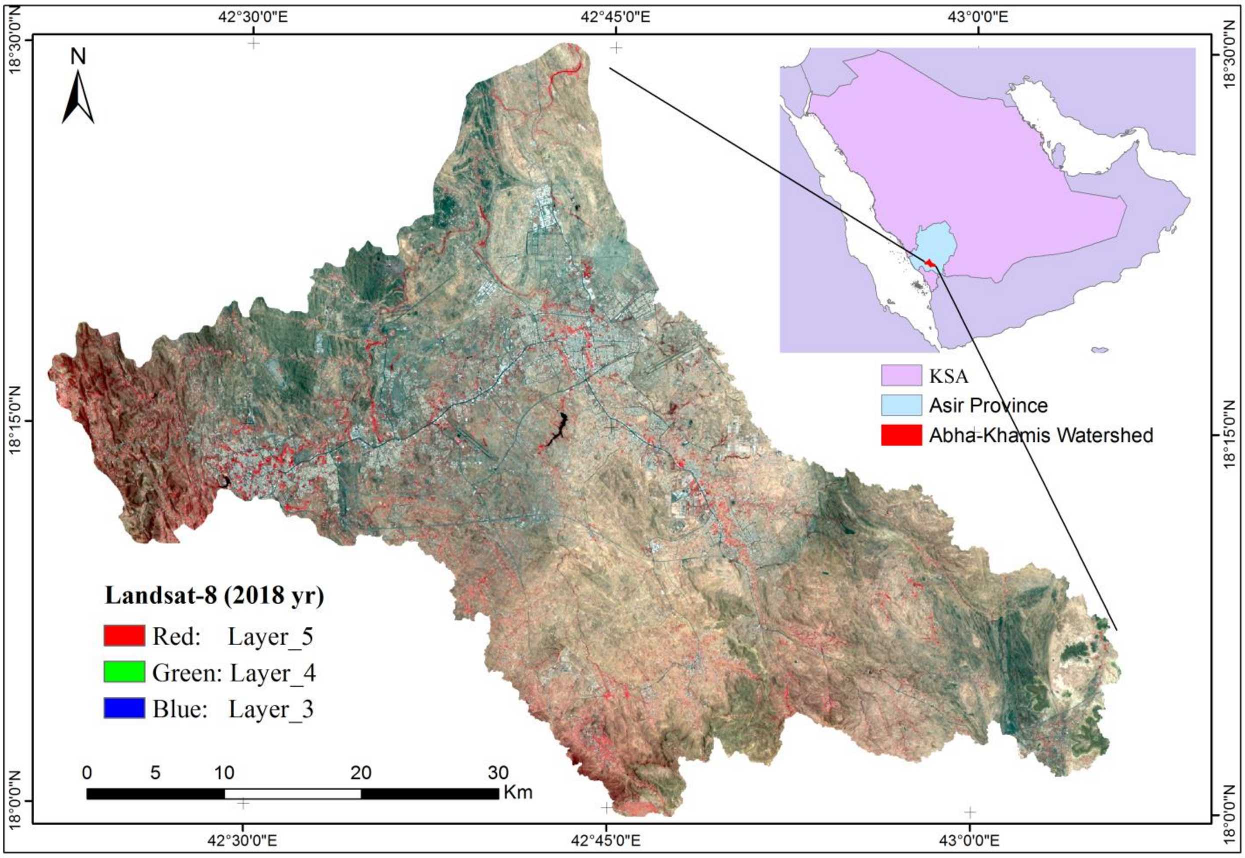

Figure 1. Study Area.

Figure 2 shows the graphical representation of minimum, maximum, and mean month-wise rainfall for last 40-year average. It is inferred from the figure that April month recorded as Maximum monthly rainfall of 193.5 mm from last 40 years whereas its mean was 45.4 mm. However, the low monthly rainfall occurred on November of 37.6 mm from the last 40 years. The highest rainfall occurred in the study during March, April, May, and August. Figure 3 shows the maximum day-wise rainfall raining from last 40 years period. It is depicted from the assessment and graph representation that on 3 February 1983 had received the maximum rainfall of 99 mm followed by 18th April 1988 of 70 mm.

Abha and Khamis-Mushait is the most densely populated city with approximately 10.3 lakh inhabitants in 2019 [https://www.stats.gov.sa/] in the southern part of Saudi Arabia. The Khamis-Mushait was considered a commercial city with large manufacturing areas, such as cement, chemicals, lubricants, marble, dyes, and glass as well as numerous industries. Since Khamis-Mushait city is the center of Saudi Arabia's southern region, it includes various workshops such as maintenance of vehicles, blacksmiths, heavy machinery, plumbing, etc. The city also has many markets and large dumping sites for the dumping of domestic waste from restaurants, homes, service centers, etc. In addition, the city is surrounded by a number of farms growing different crops.

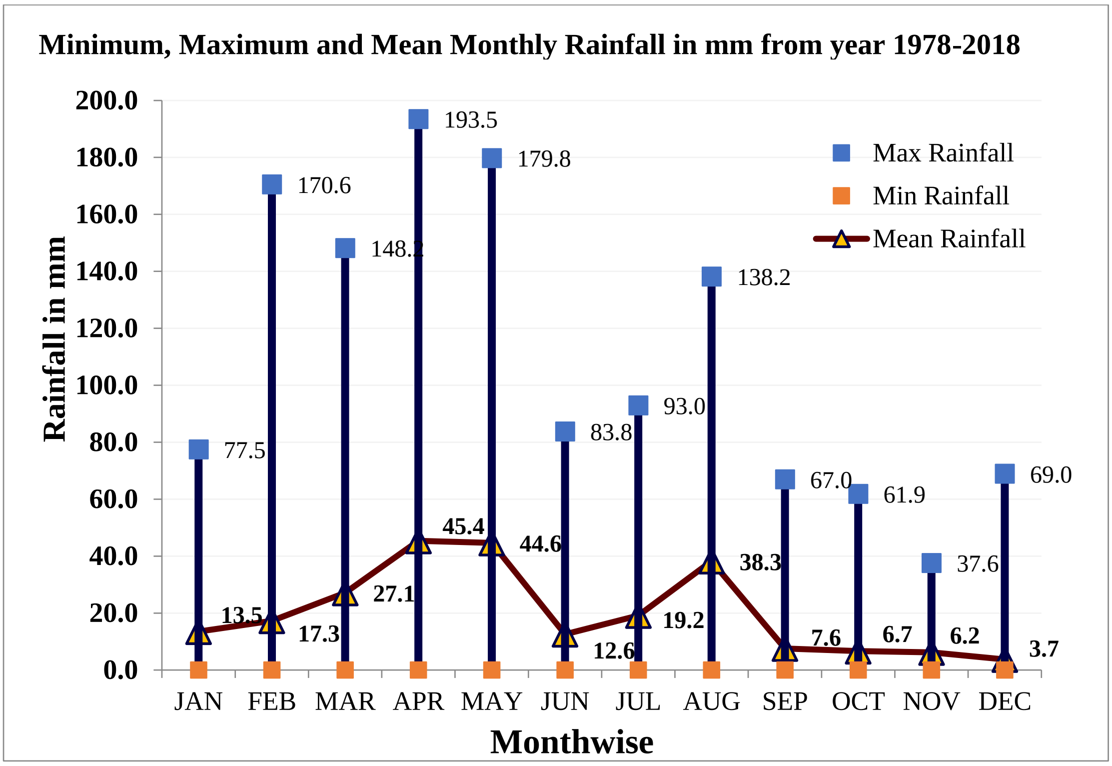

Figure 2. Minimum, Maximum, and Mean Monthly Rainfall in mm from the year 1978–2018.

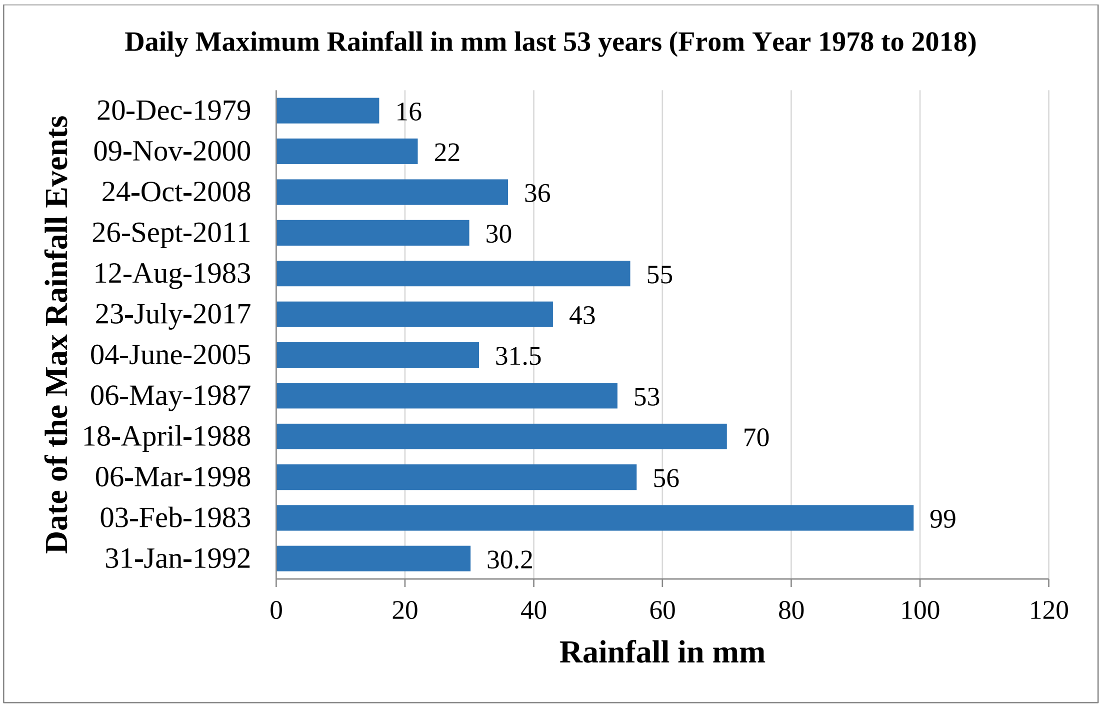

Figure 3. Daily Maximum Rainfall in mm last 53 years (From the Year 1978 to 2018).

Saudi Arabia is the largest nation in the Arab Gulf, accounting for about 80 per cent of the total land area of the Arab Peninsula. Saudi Arabia's total land area is estimated at 2.15 million square kilometers [86]. While the majority of this country's land is deserted, approximately 40 per cent of this region consists of rangeland and 1 per cent of forests [86].

Most of the cities generate around 9 million tons of municipal solid waste annually, while overall Saudi Arabia produces about 14 million tons per year by 2010, which averages of about 1.4 kg/capita/day [29]. By 2015, the average level of waste generation reached up to 15 million tons annually, or around 1.8 kg/capita/day [29].

The major ingredients of the Saudi Arabian MSW are food waste (40–51%), paper (12–28%), cardboard (7%), plastics (5–17%), glass (3–5%), wood (2–8%), textile (2–6%), metals (2–8%), etc., depending on the population density and urban activities of the area" [29]. The above information reveals that organic waste is the largest percentage in Saudi Arabia. MSW has good potential for biological waste-to-energy processes in Saudi Arabia [29].

Local municipalities in each area are responsible for the management of solid waste. In Saudi Arabia, municipal solid waste is collected from different bins and households and sent to a dump or landfill site [88]. There are currently insufficient technologies in the existing waste management system to produce some kind of monetary gain from waste obtained from different urban areas [28]. It is attributed to inadequate waste treatment systems, waste disposal systems and a lack of tipping charges [28]. Depending on its source, solid waste generation can be subdivided into residential and non-residential. In general, residential waste is referred to as household waste, while non-residential waste includes commercial, light industrial, and other waste [29]. Residential-generated waste is typically measured in kilograms per capita per day [29]. This method is ideal for use in the measurement of disposal facilities and the recovery of resource for gross estimates but is not ideal for the design of collection systems [28]. Collection systems are designed more accurately, using the average annual weight (pounds) per household (or stop) per week (PPHW) [28]. Estimates for producing household waste should be based on the actual calculation. This means that households are counted directly on residential routes and the waste collected is weighed [29]. The large quantity of waste produced in Saudi Arabia's cities is causing alarming deterioration in environmental and health problems. The problem is further compounded by the fact that national, regional, and local municipalities are actively delaying the development of long-term sustainable solutions in favor of short-term responses.

Local affairs and the Ministry of Municipalities generally regulate the MSW produced, while the management is carried out by local municipalities, including the collection, transport, and disposal of waste to landfills or dumpsites without the recovery of material or energy [89], Figure 4 shows the graphic representation of MSW generation quarter-wise in Khamis-Mushyet City. The MSW data produced was obtained from local municipalities (Abha and Khamis-Mushayet). It shows that the quarter-wise generation of waste is steadily increasing over the course of 2019. Distribution of waste generation is uneven throughout the year from 2015–2019. Therefore, the nature of waste generation does not depend on the season or months. This information supported by the statement that MSW has good potential for biological waste-to-energy processes in Saudi Arabia [29]. The Regulation of the Municipal Solid Waste Management System for Saudi Arabia can be accessed https://www.ecolex.org/details/legislation/regulation-of-the-municipal-solid-waste-management-system-lex-faoc181693/.

Figure 5 shows the MSW generation year-wise graphical representation in Khamis-Mushyet City. The MSW generation recorded the highest waste generation of 914,218 kg in 2016, while the MSW generation recorded a low waste generation of 912,350 kg in 2015. The waste generation accounted for 913,578 kg in 2018. Figure 6 shows the MSW generation year-wise graphic representation in Abha City. In 2016, the MSW generation recorded the lowest waste generation of 153,000 kg, while in 2017 it recorded the highest MSW generation of 192,000 kg. In 2018, the waste generation accounted for 155,000 kg. This may be due to awareness of solid waste generation and initiative from the government under the national transform program [90] to reduce food loss and waste.

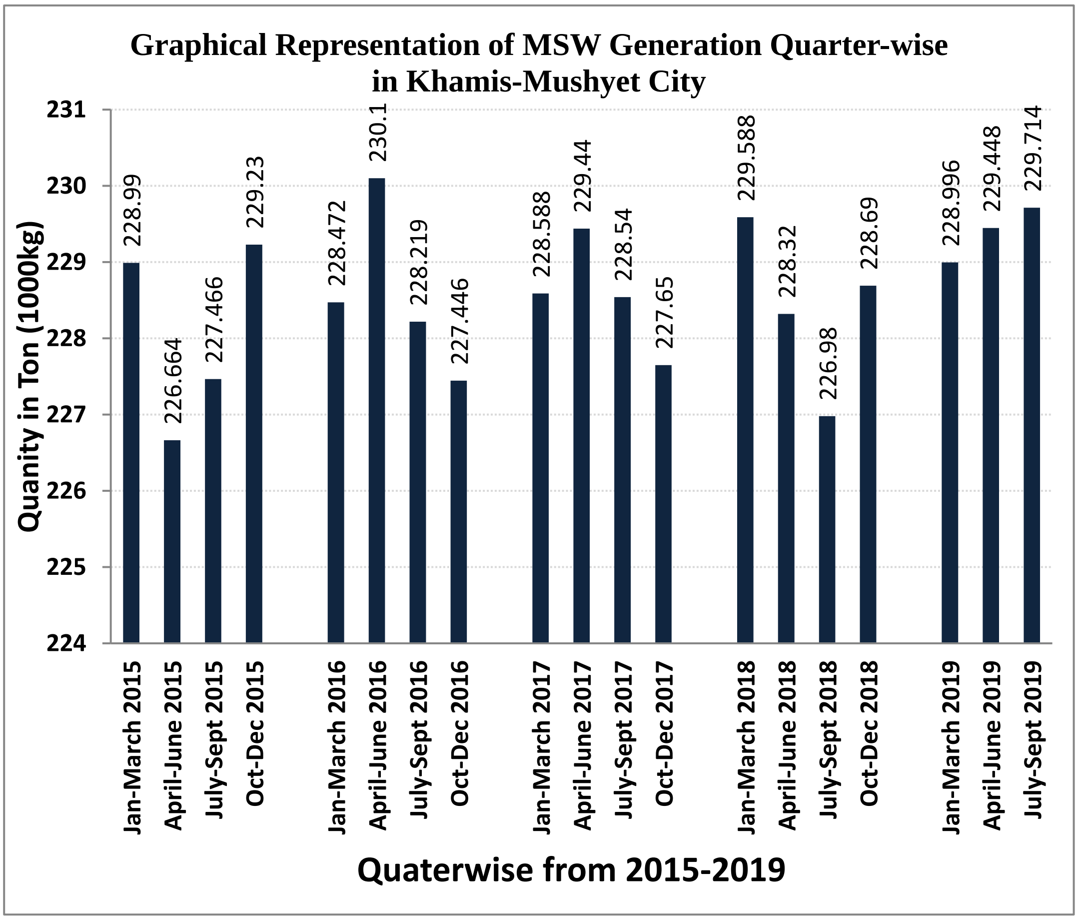

Figure 4. Graphical Representation of MSW Generation Quarter-wise in Khamis-Mushyet City.

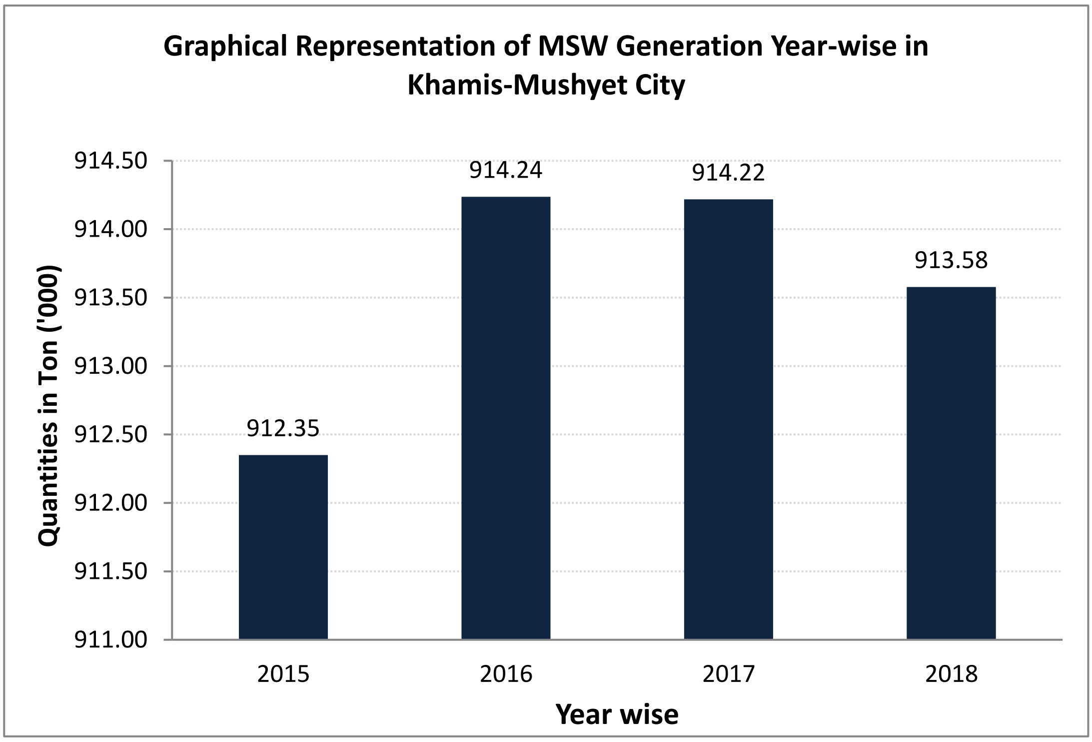

Figure 5. Graphical Representation of MSW Generation Year-wise in Khamis-Mushyet City.

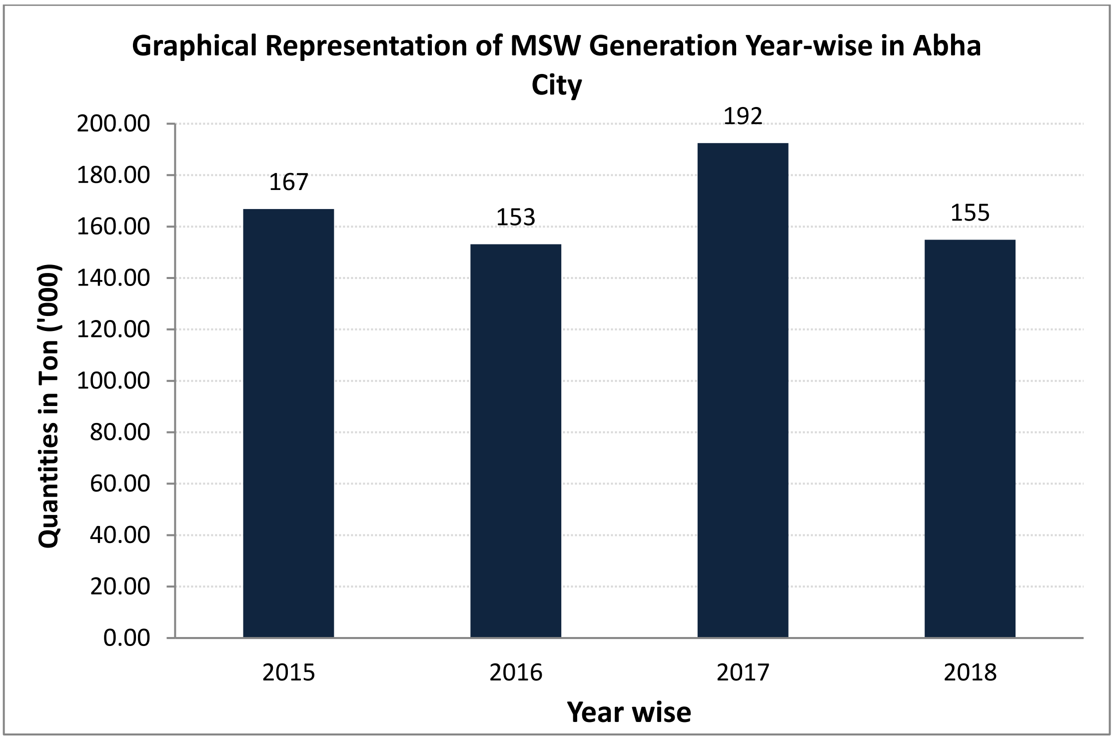

Figure 6. Graphical Representation of MSW Generation Year-wise in Abha City.

4. Materials and Methods

Current research demonstrates the use of different sources of information for potential landfill sites zonation assessment in the Abha-Khamis watershed. Regardless of how urban solid waste is handled, the final disposal of residual waste in landfills sites must be achieved [12]. Landfill site selection is a difficult process in which environmental, land use/land cover, zoning, air quality, and geotechnical parameters have to be considered [31]. The landfill will be capable of storing all the waste to be collected within 20–25 years. The relative importance of individual themes in landfill areas was derived from the knowledge of influencing factors, experts' opinion, and the practical experience. A list of questionnaires was sent to the international experts, five of which were answered. These five international experts in waste management have further discussed the relative importance of several variables (evaluators of sites) that could affect potential landfills. In addition, municipalities, stakeholders, environmental health engineering professors have also been consulted on their views regarding the relative importance of theme and their feature classes. Following the extensive literature review and expert opinion, 10 themes were selected for this research such as drainage density, land use/land cover (LULC), slope, elevation, lineament density, Normalized Difference Vegetation Index (NDVI), rainfall, distance from the airport, distance from road, and geology. These themes have been developed through RS (remote sensing) and conventional data. All the data collected were geometrically rectified to a common projection, (UTM) based on the topographical base map and GPS point, and it was resampled using the nearest-neighbor algorithm in the ERDAS Imagine software. The methodology used in the study region for modeling suitable landfill site selection is shown in Figure 7.

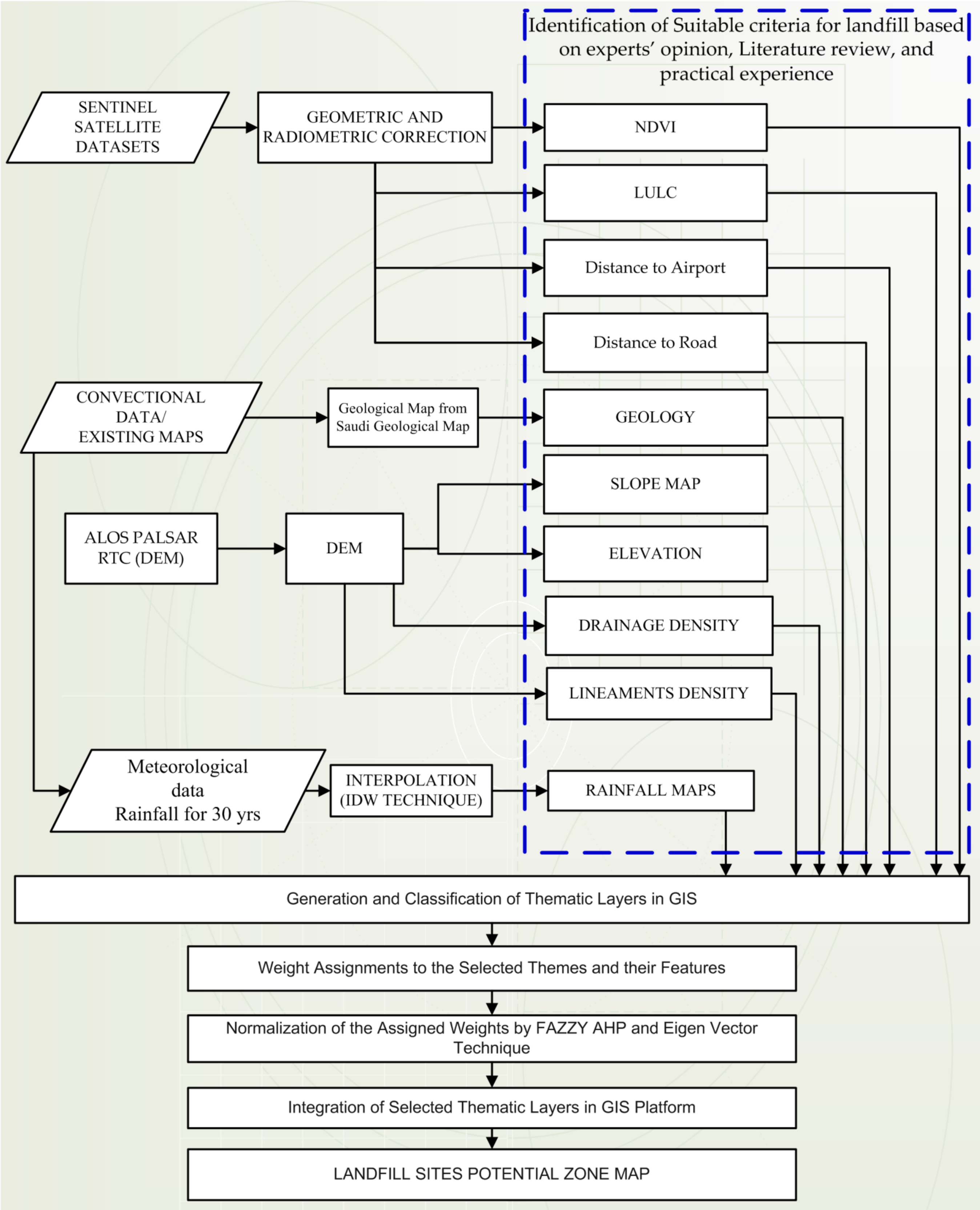

Figure 7. The methodology used in the study region for modeling suitable landfill site selection.

4.1. Data and Material Used

Meteorological data, Precipitation data collected by the Presidency of Meteorology and Environment (PME) of Saudi Arabia from 1978 to 2018 (40 years) from 13 rain gauge stations located in and near the watershed area. *Satellite images:* Sentinel-2 cloud-free data with 10 m spatial resolution acquired on 8 February 2019 was obtained from the archives of the United States Geological Survey website [91]. The digital elevation model (DEM) [92] ALOS PALSAR RTC (radiometrically terrain corrected) with a resolution of 12.5 m was obtained from NASA's Earth Science Data Systems. *Field survey*, reconnaissance survey was performed during the 01–12 February 2019 from the different locations to verify the different LULC classes, and also identifies the location of existing landfills. The data processing is done by ArcGIS 10.3; ERDAS, ENVI and Microsoft office software and SPSS software.

Topographic elevation, slope, and drainage density were generated from ALOS PALSAR RTC (radiometrically corrected) DEM data, while the other maps were created using Sentinel 2 satellite data and conventional data such as rainfall, airport distance and road network. All datasets were resampled to a spatial resolution of 10 m using the nearest neighbourhood algorithm.

Landuse: Landuse is being used to address the unwanted facility to satisfy people. In reality, the low-value land use in public view causes less resistance to landfill locations [93]. As international practices for the selection of landfill site, landfill site may not be chosen for certain land uses, including agriculture and forestry. The maximum likelihood classification (MLC) (supervised classification) was used to create the LULC map [94]. The uncertainty or error matrix is used to verify the results of the classification [95] and has been established with a good agreement (overall accuracy and Kappa coefficient of 91.32 and 0.8915 respectively). The study area's LULC map is shown in Figure 8a. Scrubland (41.1%) is the most prevalent class, led by built-up (18.1%), exposed rock (17.8%), sparse vegetation (9.9%), and bare soil (8.9 percent) (8.9 percent). The high weight is allocated to the exposed rock, bare soil, and scrubland. The low weight is consigned to agricultural land, dense vegetation, built-up class, and water bodies.

Elevation: Slope and land elevation are considered to be essential parameters for landfill site [96]. The topographic elevation is liable to regulate important parameters for prospects of landfill sites and is influenced by various hydrogeological and geomorphological processes (i.e., weather data, geology, environmental degradation, etc.) [97]. The DEM for the study area was generated from ALOS PALSAR RTC data [92]. DEM obtained from the website of NASA (ESDS) was unfilled and unprocessed and hence the DEM was cleaned to cover up local depressions by filling sinks. The elevation of the study area varies from 1888 to 2995 m with a mean value of 2180 m as shown in Figure 8b. The higher elevation situated west and southeast, while north of the map the lower elevation was found. High weight for lower elevation and low weight for higher elevation are assigned while assigning the weight to delineate the landfill site zone [98].

The slope is an important determinant of many landscape processes including soil water quality, erosion risk, and surface runoff. The slope is very significant in the design of landfill sites, as its stability forms an important part of the material weight at the landfill site. From a cost-construction perspective, the slope is an important, critical element. Very steep slopes can result in higher diggings costs [99]. ALOS PALSAR RTC DEM data was used to compute pixel-based terrain slope ranging from 0° to 68°. Based on the above considerations, weight values with a slope value of 30–68° were classified the lowest and low slope (0–10°) areas considered to be very suitable and assigned the highest weight values [57,99,100]. A slope map was prepared using the ArcGIS 3D analyst (Figure 8c).

Drainage Density: Amongst the most significant considerations in landfill site selection is possible to surface water pollution; therefore, landfills should not be near-surface water sources (ponds, lakes, and streams). Landfill causes harmful leaks and emissions that are not expected to reach water resources, such as wadies and wetlands. Low drainage density areas must therefore be observed in landfills construction. The drainage density is the sum of the length of all streams (wadis) in a watershed divided by the total area of the watershed [101]. High weight attributed to low drainage density and low weight attributed to high drainage density for landfill suitable sites. A drainage density map was prepared using the ArcGIS spatial analyst (Figure 8d).

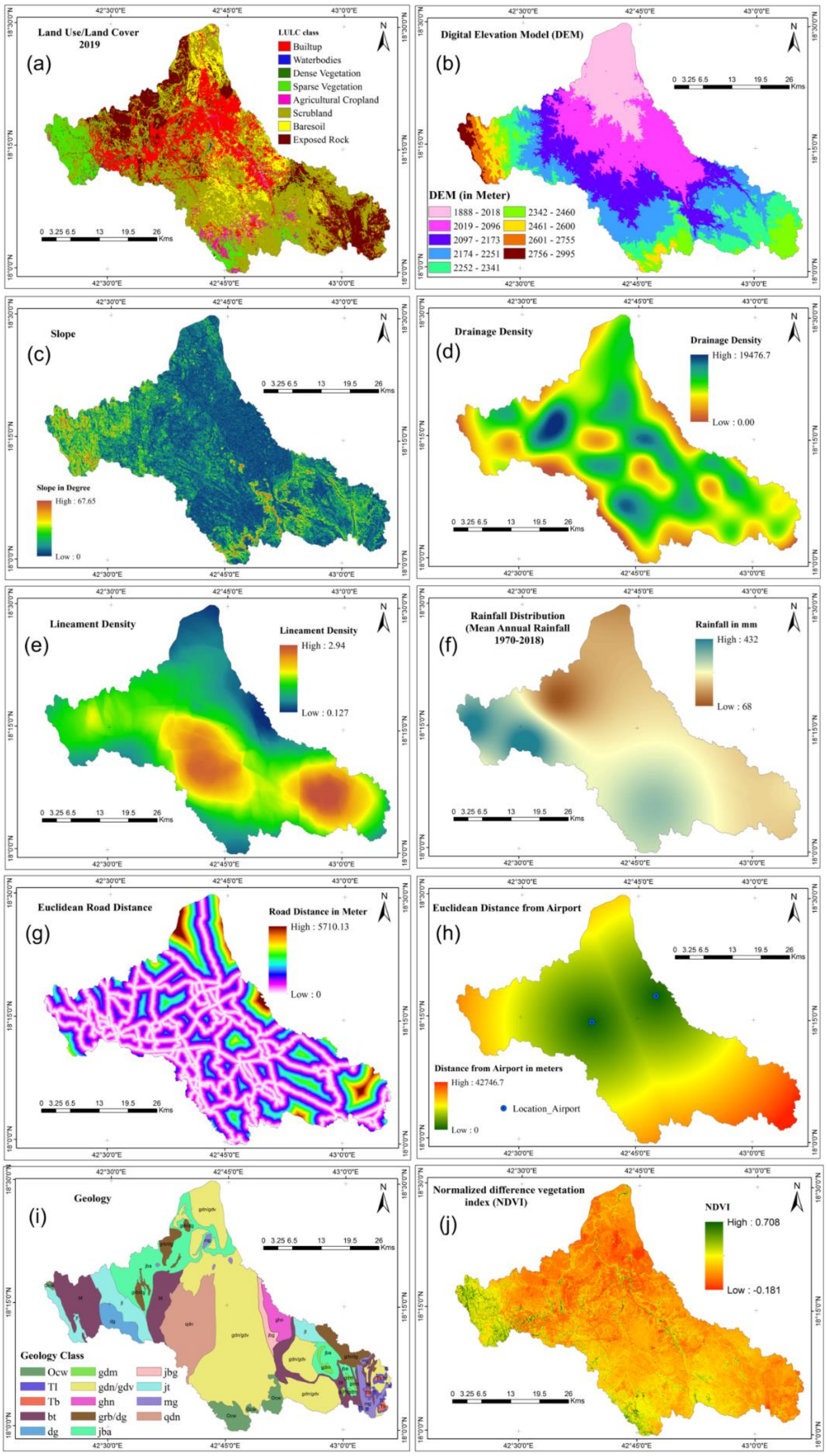

Figure 8. Showing the landfill site suitability factors, such as (**a**) land use/land cover (LULC), (**b**) digital elevation model (DEM), (**c**) slope, (**d**) drainage density, (**e**) lineament density, (**f**) rainfall, (**g**) Euclidean road distance, (**h**) Euclidean airport distance, (**i**) geology, (**j**) normalized difference vegetation index (NDVI).

Lineament density: Lineaments are key groundwater controls in any underground environment. Being poor areas, they typically act as conduits for sub-surface movement or accumulation of groundwater. It is therefore pragmatic that no landfill site is located around a high lineament density, as this may lead to significant contamination of groundwater supplies by leaching. Visual interpretation methods [102] using the Sentinel 2 satellite data and geological map were used to extract the lineaments map. High lineament density regions tend to support the high groundwater availability [103]. Therefore, landfills should be located in areas with low lineament density (Figure 8e).

Rainfall: Rainfall was included in the climatic parameters in the selection of landfill sites. Landfill areas with high rainfall are not appropriate [73]. Infiltration rate depends largely on rainfall. "Infiltration is a significant factor in determining possible groundwater contamination risk, which is increased and decreased by rainfall and surface runoff, thus, it is a major criterion to be considered for landfill framework development.

Road network: Esthetic concerns would be advisable for good planning, and landfill sites should be accessible under any conditions [51,104]. The further out of the landfill site is off the road and it is difficult to access landfill, therefore it will increase the costs associated with transportation and is of little benefit to the authorities involved with waste management. Deposits nearer to the road, however, render an esthetically bad view. Road distribution can be extracted by integrating remote sensing and topographic maps following buffer analysis. The Euclidean distance was used to assess distances from or outside the road network (Figure 8h). The first control point (nearer to the road) indicates the most suitable distance to the landfill site, while the second control point (far from road network) indicates the least favorable distance to the landfill site (Figure 8g).

The landfill site should be located outside the 20 km radius of any airport/airbase to prevent birds from disrupting aircraft during landing and take-off (Figure 8f).

Geology: Dependent geological units are the best waste disposal sites [105]. Areas vulnerable to landslides, volcanoes, erosion, earthquakes, subsidence and in particular karst creation should be completely ignored in site selection processes. It is desired to have homogeneous, massive, and almost impermeable clay and shale units will provide a broad vertical separation between the landfill base and the upper aquifer [106]. The study area is situated in a landfill site on the suitability of geomaterials (Figure 8i), and the lithological units can be divided into seven groups as follows (Table 2):

4.2. MCDM: Fuzzy Set Theory

Zadeh's "Fuzzy set theory" in MCDM [107] is a modeling technique that simulate a complex system that is not easy to define in crisp numbers. The Fuzzy set theory [107] was commonly used to model decision-making processes based on ambiguous and imprecise data such as decision-maker preferences. Fuzzy offers a remarkably simple way to draw precise conclusions from uncertainty, vagueness, and inaccuracy [108]. When making choices to perform a spatial object on a map as a member, fuzzy logic is included for spatial planning. In classical set theory, also called crisp, an entity is either part of a set or not part of a set. "Since a feature object can be used as membership values between 0 and 1 by fuzzy set theory, this represents the degree of membership function [107]". A triangular fuzzy number (TFN) M is shown in Figure 9 as below mentioned.

"TFNs are expressed by (l/m, m/u) or (l, m, u), the lowest possible value, the highest possible value, respectively, the TFN has a linear representation on its right and left sides during its membership term (Equation (1))"

$$\mu\left(x\backslash\widetilde{\mathrm{M}}\right) = \left\{ \begin{array}{cc} 0, & x < l, \\ (x-l)/(m-l), & l \le x \le m \\ (u-x)/(u-m), & m \le x \le u \\ 0, & x > u \end{array} \right\} \quad (1)$$

"The following equation shows the fuzzy number of each membership level based on its left and right representation [109].

$$\widetilde{\mathrm{M}} = \left(M^{l(y)},\ M^{r(y)}\right) = (l + m - l)\ y,\ u + (m - u)y) \tag{2}$$

where $l(y)$ and $r(y)$ represent a fuzzy number's left and right sides, respectively."

Table 2. Geological unit of the study area (coding nomenclature is as per the Saudi geological survey).

Head	Geological Code	Description
Dioritic and Gabrioc rocks	mg/mgy	"Metagabbro and Gabbro- Metagabbro (mg) mixture formed of gabbro sheets and irregular bodies within diorite (dgb) or within metamorphic rocks (mgy)"
	gb	"Gabbro—Massive to layered plutons, sills, dikes, and irregular bodies
Basalt and Andesite	jt	Basalt- Pillow lava and Andesite-Pillow lava, tuff, decite tuff, flow breccia, carbonaceous conglomeratic greywacke, phyllite and interbedded subordinate"
	bt	"Bahah Group within the Tayyah Belt-volcaniclastic graywacke, subordinate chert, slate and conglomerate, carbonaceous shale and siltstone, minor interbedded basalt, andesite and dacite"
Biotite-Quartz, anabiotite schist, Tonalite Suite	jba	"Biotite-Quartz-Plagioclase Granofels-Subordinate amphibolite, anabiotite schist"
	jbg	"Biotite-Quartz-Plagioclase Granofels-Subordinate amphibolite, anabiotite schist"
	qdn	"Hornblende-Biotite Tonalite-Gneissic tonalite (gdn); hornblende diorite associated with hornblende-biotite (di2)"
Granodiorite and Granite Suite	ghn	"Biotite-Hornblende Granodiorite-Foliated"
	gdm	"Muscovite-Biotite Granodiorite-Gneissic"
	gdn/gdv	"Biotite Granodiorite and Monzogranite-Foliated uniform body (gdn); mixture formed of irregular layers and bodies in amphibolite (gdv)"
	grb/dg	"Biotite Monzogranite-Uniform body (grb), mixture formed of dikes, sheets and irregular bodies within tonalite and trondhjemite (gt) or with diorite and gabbro (dg)"
Sedimentary, Volcanic and Metamorphic Rocks	Ocw	Wajid Sandstone
	Tb	Tertiary Basalt
	TI	Tertiary Laterite

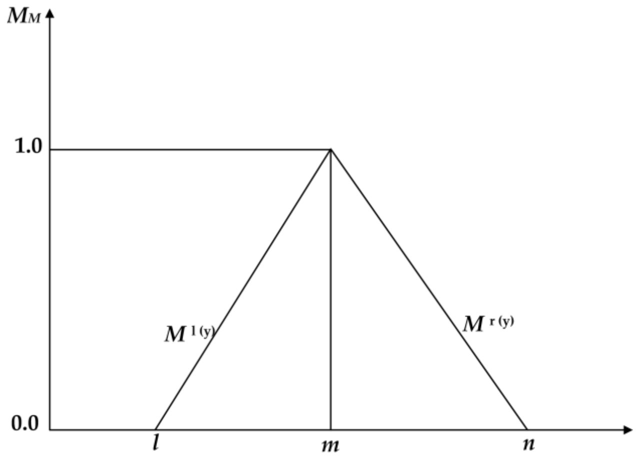

Figure 9. A triangular fuzzy number (TFN) $\widetilde{\mathrm{M}}$.

4.3. Fuzzy Membership Function (FMF)

The "Fuzzy set theory" and Fuzzy Membership Function (FMF)'s primary role can indicate ambiguous data. Mathematics and coding functions can also be used in a fuzzy environment. "The fuzzy set is an object class defined by a membership function, assigning a membership value from 0 to 1 for each object, and vice versa [107], For landfill site mapping, the fuzzy set theory makes the definition of a partial location membership considered for multi-class mapping, in this conceptual context, the FMFs have been allocated to the study of spatial variance, and their pattern has led to the creation of fuzzy boundaries for each potential zone". The variance has been allocated to FMFs, and its trend has resulted in fuzzy boundaries for each potential zone being established. The transitions from 1 to 0 are being identified by applying the form of each FMF.

4.4. Feature Data Standardization Using FMFs

Mapping of possible landfill sites, feature classes generated in various units as well as measurement levels. Four estimation scales, defined as nominal, ordinal, ratio and interval [110], which require data standardization. For this purpose, the evaluation process includes the integration of all impact factors for possible landfill thematic layer sites in one output. Standardization approaches have therefore been taken into account by a fuzzy membership approach. The use of fuzzy set theory in mapping potential landfill sites was seen as a better outcome [111]. As a result, all suitable site factors for landfills ranged from low suitable (0) to high suitable (1). In the present study, two membership functions used for the suitable landfill site, viz., according to the goals and hypothesis. "The linear FMF (linear decrease or increase in membership between two inputs: linearized sigmoid shape) and categorical FMFs (the expert assigned membership value for each designated class) (Table 3), the first two sigmoidal membership characteristics are commonly used in many fuzzy logic applications and allow for a progressive transition from 0 (non-member) to 1 (full membership) [110], although it is often unavoidable to choose user-defined or categorical membership functions". Table 3 shows membership functions relied on Fuzzy-AHP, such as "(Type I) Linear FMFs" for drainage density, lineament density, rainfall, slope, elevation, distance from road and distance from the airport, and "(Type II) Categorical FMFs" for LULC and Geology. All the criteria used for the FMF and subsequent Table 3 are shown below.

Table 3. Summary of the fuzzy standardization for the criteria.

Cluster	Criteria	"Fuzzy and Shape Membership Functions"	"Control Point/Value Point"
Environmental	Drainage density	"monotonically decreasing-linear"	a = 1000; b = 20,000
	Lineament density	"monotonically decreasing-linear"	c = 0.50; d = 2.94
	LULC	Categorical	—
	Geology	Categorical	—
	Rainfall	"monotonically decreasing-linear"	c = 0; d = 432
	Slope	"monotonically decreasing-linear"	c = 10°; d = 67.66°
	Elevation	"monotonically decreasing-linear"	a = 1888; b = 2995
	NDVI	"monotonically decreasing-linear"	
Socio-economical	Distance to Road	Symmetric-Linear	a = 300; b = 500; c = 1000; d = 2500
	Distance to Airport	"monotonically increasing-linear"	a = 8000; b = 10,000

4.5. Weights Assignments and Normalization

Five experts (environmentalists) are interviewed via a set of a questionnaire in the research areas expertise in waste management and hydro-geology specifically framed to obtain their views on the relative importance of environmental variables influencing the establishment of landfill sites. In addition, for their views on the relative importance of the subject and its feature classes, local environmentalist/hydrogeologists consulted using a focus group discussion method. Saaty [112] "suggested weight assignment, but in earlier studies, it was not considered significant". The AHP has been commonly used by the MCDA to obtain appropriate weights for different criteria [113]. AHP calculates the weights needed to support the selected matrix with the appropriate thematic layers to compare and evaluate all the parameters (thematic layers) identified [52,114]. For each decision variant (for example, for each location), weights along with the criterion values have been used to form a single scalar value, which is the relative strength of the variable. The AHP aims to consider expert expertise and since traditional AHP does not accurately reflect the human option. The Fuzzy upgrading of AHP (called Fuzzy-AHP) was developed in order to deal with the fuzzy hierarchical issues. For this study, it used the Fuzzy-AHP method to fuzzy hierarchical analysis by allowing fuzzy numbers in combination to determine fuzzy weights. The following steps were considered in order to determine the weights of the assessment criteria with a FAHP [115]. ***Step I:*** All parameters in the dimensions of the hierarchy structure have been used to create pairwise comparison matrixes. In each case, which of the two parameters was more important, the linguistic concepts were applied to the pair-wise evaluations as follows:

$$\text{“}\widetilde{A} = \begin{bmatrix} \widetilde{1} & \widetilde{a}_{12}\cdots & \widetilde{a}_{1n} \\ \widetilde{a}_{21} & \widetilde{1} & \widetilde{a}_{2n} \\ \vdots & \vdots\ddots & \vdots \\ \widetilde{a}_{n1} & a_{n2}\cdots & \widetilde{1} \end{bmatrix} = \begin{bmatrix} \widetilde{1} & \widetilde{a}_{12}\cdots & \widetilde{a}_{1n} \\ 1/\widetilde{a}_{21} & \widetilde{1} & \widetilde{a}_{2n} \\ \vdots & \vdots\ddots & \vdots \\ 1/\widetilde{a}_{n1} & 1/a_{n2}\cdots & \widetilde{1} \end{bmatrix}\text{”} \quad (3)$$

where $\widetilde{a}_{ij}$. measure denotes, let $\widetilde{1}$ be (1,1,1), when i equal j (i.e., $i = j$); if $\widetilde{1}$, $\widetilde{2}$, $\widetilde{3}$, $\widetilde{4}$, $\widetilde{5}$, $\widetilde{6}$, $\widetilde{7}$, $\widetilde{8}$, $\widetilde{9}$ measure that criterion i is relatively important to criterion j and then $\widetilde{1}^{-1}$, $\widetilde{2}^{-1}$, $\widetilde{3}^{-1}$, $\widetilde{4}^{-1}$, $\widetilde{5}^{-1}$, $\widetilde{6}^{-1}$, $\widetilde{7}^{-1}$, $\widetilde{8}^{-1}$, $\widetilde{9}^{-1}$ measure that criterion j is relatively important to criterion i Fuzzy conversion scale is described in Mallick et al. [116].”

“*Stage I* Buckley’s geometric mean method was used to determine the criterion’s fuzzy geometric mean and fuzzy weighting [117].”

$$\widetilde{r}_i = \left(\widetilde{a}_{i1} \bigotimes \widetilde{a}_{i2} \bigotimes \ldots \bigotimes \widetilde{a}_{in}\right)^{1/n} \text{And then } \widetilde{w}_i = \widetilde{r}_i \bigotimes \left(\widetilde{r}_i \bigotimes \ldots \bigotimes \widetilde{r}_n\right)^{-1} \quad (4)$$

where $\widetilde{a}_{in}$ is fuzzy comparison value of criterion i to criterion n, therefore, $\widetilde{r}_i$ is geometric mean of fuzzy comparison value of criterion i to each criterion, $\widetilde{w}_i$ i is the fuzzy weight of the ith criterion, can be shown by a TFN, $\widetilde{w}_i = (lw_i, mw_i, uw_i)$. Here lw_i, mw_i, uw_i stand for the lower, middle, and upper values of the fuzzy weight of the ith criterion, respectively”

4.6. Landfill Site Potential Zone (LSPZ) Map Development

The landfill site potential mapping (LSPM) of the study area is created by integrating feature thematic maps into GIS platform. The “weighted linear combination (WLC) aggregation method” used to calculate the LSPZ [118] using Equation (5) as below mentioned.

$$LSPI = \sum_{w=1}^{m}\sum_{i=1}^{n}(wt_j \times x_i) \quad (5)$$

“where, LSPI = Landfill site potential index, x_i = thematic maps (FMF) and wt_j = normalized weight of the j^{th} theme, m = total number of themes, and n = total number of classes in a theme.”

4.7. Sensitivity Analysis

The sensitivity test is carried out to determine the effects of the input parameters on the model output results and also to check the impact on the parameter or factor conditions improvement process [119]. Data on weighted values influence and weights assigned to each of the variable evaluated by sensitivity analysis [120]. Therefore, each criterion’s effective weights are compared to the assigned weight. Equation (6) was used to determine the weight [120].

$$Effective\_weight = \frac{Theme_{weight} \times Theme_{scaled}}{LSPI} \times 100 \quad (6)$$

“where, the weight and scaled value of the theme (theme) assigned to each pixel, respectively and LSPI is the landfill site potential index as calculated from Equation (5).”

5. Results

5.1. Weights Normalization for Thematic Maps

The fuzzy-AHP method was used to assign a weight to each theme and class. Literature survey, expert opinion, and field awareness used to assign importance to each theme in the matrix (Tables 4–6). Drainage density has been given the highest weight, as landfills cause hazardous leakage and pollution that must be prevented from entering water supplies like wetlands and wadies [48]. It is followed by LULC, Geology, distance to road, and topography (elevation).

Table 4. The ten themes' pairwise comparison matrix.

	Drainage Density	LULC	Geology	Distance Road	Elevation	Distance Airport	Slope	Lineament Density	Rainfall	Vegetation Density
Drainage Density	1,1,1,	1,3,5	2,4,6	3,5,7	4,6,8	5,7,9	6,8,9	6,8,9	7,9,9	7,9,9
LULC	1/5,1/3,1	1,1,1,	1,3,5	2,4,6	3,5,7	4,6,8	5,7,9	6,8,9	6,8,9	7,9,9
Geology	1/3.1/2,1	1/5,1/3,1	1,1,1,	1,2,3	1,2,3	1,3,5	6,8,9	6,8,9	6,8,9	7,9,9
Distance Road	1/7.1/5,1/3	1/6,1/4,1/2	1/3,1/2,1	1,1,1,	1,2,3	1,2,3	1,3,5	6,8,9	7.9.9	7,9,9
Elevation	1/8,1/6,1/4	1/7,1/5,1/3	1/3,1/2,1	1/3,1/2,1	1,1,1,	1,2,3	1,2,3	5,7,9	5,7,9	6,8,9
Distance Airport	1/9,1/7,1/5	1/8,1/6,1/4	1/5,1/3,1	1/3,1/2,1	1/3,1/2,1	1,1,1,	1,2,3	4,6,8	5,7,9	6,8,9
Slope	1/9,1/8,1/6	1/9,1/7,1/5	1/9,1/8,1/6	1/5,1/3,1	1/3,1/2,1	1/3,1/2,1	1,1,1,	2,4,6	3,5,7	4,6,8
Lineament Density	1/9,1/8,1/6	1/9,1/8,1/6	1/9,1/8,1/6	1/9,1/8,1/6	1/9,1/7,1/5	1/8,1/6,1/4	1/6,1/4,1/2	1,1,1,	1,3,5	1,2,3
Rainfall	1/9,1/9,1/7	1/9,1/8,1/6	1/9,1/8,1/6	1/9,1/9,1/7	1/9,1/7,1/5	1/9,1/7,1/5	1/7,1/5,1/3	1/5,1/3,1	1,1,1,	1,2,3
Vegetation Density	1/9,1/9,1/7	1/9,1/9,1/7	1/9,1/9,1/7	1/9,1/9,1/7	1/9,1/8,1/6	1/9,1/8,1/6	1/8,1/6,1/4	1/3,1/2,1	1/3,1/2,1	1,1,1,

Table 5. Weights using Fuzzy-AHP techniques for thematic layers.

	Drainage Density			LULC			Geology			Distance Road			Elevation			Distance Airport		
Drainage Density	0.356	0.378	0.341	0.357	0.378	0.340	0.357	0.378	0.340	0.357	0.378	0.340	0.357	0.378	0.340	0.357	0.378	0.356
LULC	0.190	0.192	0.222	0.190	0.192	0.221	0.190	0.192	0.221	0.190	0.192	0.221	0.190	0.192	0.221	0.190	0.192	0.190
Geology	0.131	0.136	0.156	0.131	0.137	0.156	0.131	0.137	0.156	0.131	0.137	0.156	0.131	0.137	0.156	0.131	0.137	0.131
Distance Road	0.075	0.074	0.077	0.075	0.074	0.077	0.075	0.074	0.077	0.075	0.074	0.077	0.075	0.074	0.077	0.075	0.074	0.075
Elevation	0.062	0.058	0.060	0.062	0.059	0.060	0.062	0.059	0.060	0.062	0.059	0.060	0.062	0.059	0.060	0.062	0.059	0.062
Distance Airport	0.051	0.047	0.050	0.051	0.048	0.050	0.051	0.048	0.050	0.051	0.048	0.050	0.051	0.048	0.050	0.051	0.048	0.051
Slope	0.040	0.036	0.035	0.040	0.036	0.035	0.040	0.036	0.035	0.040	0.036	0.035	0.040	0.036	0.035	0.040	0.036	0.040
Lineament Density	0.031	0.027	0.023	0.031	0.027	0.023	0.031	0.027	0.023	0.031	0.027	0.023	0.031	0.027	0.023	0.031	0.027	0.031
Rainfall	0.030	0.024	0.020	0.030	0.024	0.020	0.030	0.024	0.020	0.030	0.024	0.020	0.030	0.024	0.020	0.030	0.024	0.030
Vegetation Density	0.030	0.023	0.018	0.030	0.023	0.018	0.030	0.023	0.018	0.030	0.023	0.018	0.030	0.023	0.018	0.030	0.023	0.030

Table 6. Weights using Fuzzy-AHP techniques for thematic layers.

	Slope			Lineament Density			Rainfall			Vegetation Density			*l*	*m*	*n*	*Defuzzy*	*Weight*
Drainage Density	0.357	0.378	0.340	0.357	0.378	0.340	0.357	0.378	0.340	0.357	0.378	0.340	0.3567	0.3783	0.3403	0.358	35.92
LULC	0.190	0.192	0.221	0.190	0.192	0.221	0.190	0.192	0.221	0.190	0.192	0.221	0.1899	0.1920	0.2214	0.201	20.15
Geology	0.131	0.137	0.156	0.131	0.137	0.156	0.131	0.137	0.156	0.131	0.137	0.156	0.1310	0.1367	0.1557	0.141	14.14
Distance Road	0.075	0.074	0.077	0.075	0.074	0.077	0.075	0.074	0.077	0.075	0.074	0.077	0.0752	0.0738	0.0772	0.075	7.55
Elevation	0.062	0.059	0.060	0.062	0.059	0.060	0.062	0.059	0.060	0.062	0.059	0.060	0.0619	0.0586	0.0599	0.060	6.03
Distance Airport	0.051	0.048	0.050	0.051	0.048	0.050	0.051	0.048	0.050	0.051	0.048	0.050	0.0508	0.0475	0.0503	0.050	4.96
Slope	0.040	0.036	0.035	0.040	0.036	0.035	0.040	0.036	0.035	0.040	0.036	0.035	0.0396	0.0356	0.0348	0.037	3.68
Lineament Density	0.031	0.027	0.023	0.031	0.027	0.023	0.031	0.027	0.023	0.031	0.027	0.023	0.0310	0.0272	0.0234	0.027	2.72
Rainfall	0.030	0.024	0.020	0.030	0.024	0.020	0.030	0.024	0.020	0.030	0.024	0.020	0.0303	0.0240	0.0200	0.025	2.48
Vegetation Density	0.030	0.023	0.018	0.030	0.023	0.018	0.030	0.023	0.018	0.030	0.023	0.018	0.0299	0.0227	0.0185	0.024	2.37

Statistical analysis i.e., consistency ratios <9.0%, delta = 4.3×10^{-8} to 7.3×10^{-8}, principal eigen value of 11.20; Eigenvector solution: 7–9 iterations for allocated weights for the ten thematic layers and their characteristics show that the assigned weights are compatible with the expected outcomes.

5.2. Sensitivity Analysis

Table 7 statistical analysis (from Equation (6)) confirms significant variations in LSPI also infers the effective weights with the theoretical weight for each landfill site parameter. Table 7 illustrates the important LSPI variance confirmed by statistical analysis (derived from Equation (6). This is anticipated after drainage density criteria have been removed, as the layer has the highest indices of variation (37.88%). The LSPI also seems to be sensitive to LULC, geology, and Distance to road (with an average variation of 18.78%, 14.86%, and 7.21%, respectively). This may be because of the high theoretical weight of all of these parameters (20.15%, 14.14%, and 7.55%). Removal of elevation (DEM), distance to the airport, slope, lineament density, rainfall and vegetation density also led to the sensitivity value variations in the study area; their mean value is 5.99%, 4.45%, 3.42%, 2.91%, 2.32%, and 2.18%, respectively. The effective weights for each theme, however, are slightly different from the theoretical weight assigned to the area of the suitability of the landfill site.

Table 7. Comparison of theoretical weight and effective weight.

Sl. No	Feature Layers	"Theoretical Weight (%)"	"Effective Weight (%)"			
			Min.	**Max.**	**Mean**	**Std. Dev.**
1	DD	35.92	2.18	71.31	37.88	9.395
2	LULC	20.15	0.00	41.65	18.78	9.460
3	Geology	14.14	0.00	40.85	14.86	5.568
4	Distance to Road	7.55	0.00	26.85	7.21	5.573
5	Elevation (DEM)	6.03	0.02	22.27	5.99	2.697
6	Distance to Airport	4.96	0.00	18.69	4.45	3.569
7	Slope	3.68	0.00	16.71	3.42	1.472
8	Lineament Density	2.72	0.00	7.66	2.91	1.323
9	Rainfall	2.48	0.00	8.35	2.32	0.834
10	Vegetation Density	2.37	0.00	7.54	2.18	0.635

5.3. Analysis of LSPZ Classification Map

With the daily increase in waste generation and losing land availability for waste disposal in Abha-Khamish twin cities within the studied watershed, it is a vital job to manage excessive waste regular basis. The findings of the study summarize the weighted overlay analysis technique using GIS-based Fuzzy-AHP as the most effective methods for mapping potential landfill sites. Ten (10) thematic layers; drainage density, LULC, geology, distance road, elevation, distance airport, slope, lineament density, rainfall, and vegetation density, classifying the study area into various landfill sites potential zones (Figure 10). Figure 11 shows the LSPZ map, quantitatively developed for analysis using the landfill site potential index (LSPI). The landfill sites potential index's mean value of 0.584 with standard deviation of 0.105, minimum and maximum LSPI were 0.22 and 0.92, respectively.

LSPI is classified into zones by histogram profile. The histogram profile shows the data distribution frequency LSPI value. Figure 12 demonstrates uneven distribution values. Therefore, the natural break classification for zoning mapping was adopted. Subsequently, potential landfill sites were identified and divided into five classes: namely very low suitable (fuzzy value 0.20–0.45), low suitable (0.46–0.55), moderately suitable (0.56–0.65), high suitable (0.66–0.75), and very high suitable (0.76–0.92). Statistics on integrated landfill categories for potential landfill sites are shown in Table 8. According to the statistical analysis, 23.91% and 3.67% of the total area were under good and very good LSPZ, while 22.84% and 38.14% accounted to the poor and moderate potential zone, respectively. As a quality-based zoning, the existing two landfill sites were located over a very low suitable and low suitable potential area whereas 1 landfill site was located over the high suitable. The spatial variance of high and very high potential landfill site zones found in the north-eastern, east-central, and south-eastern parts of the watershed.

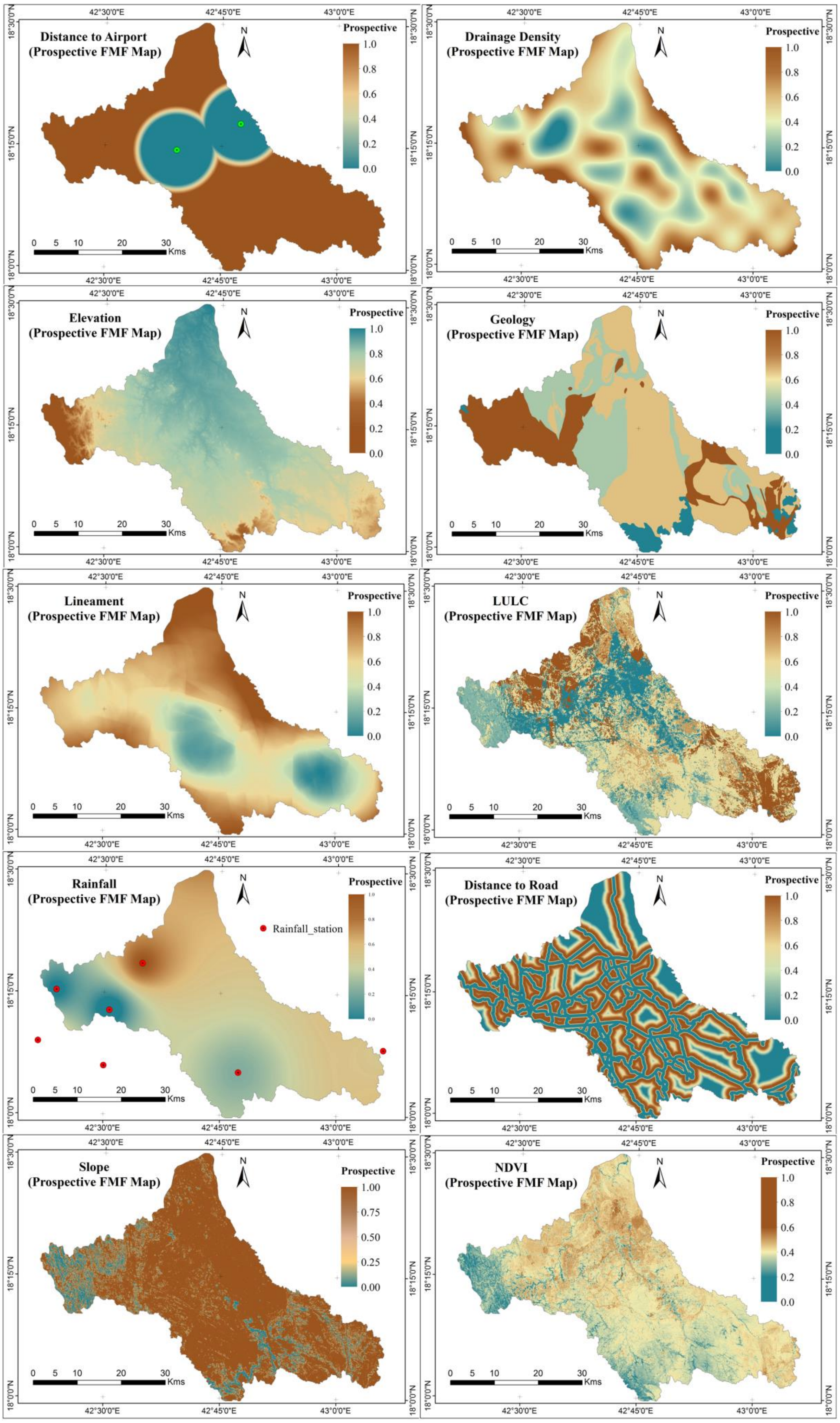

Figure 10. Thematic layers for landfill site potential area based on Fuzzy Membership Functions (FMFs).

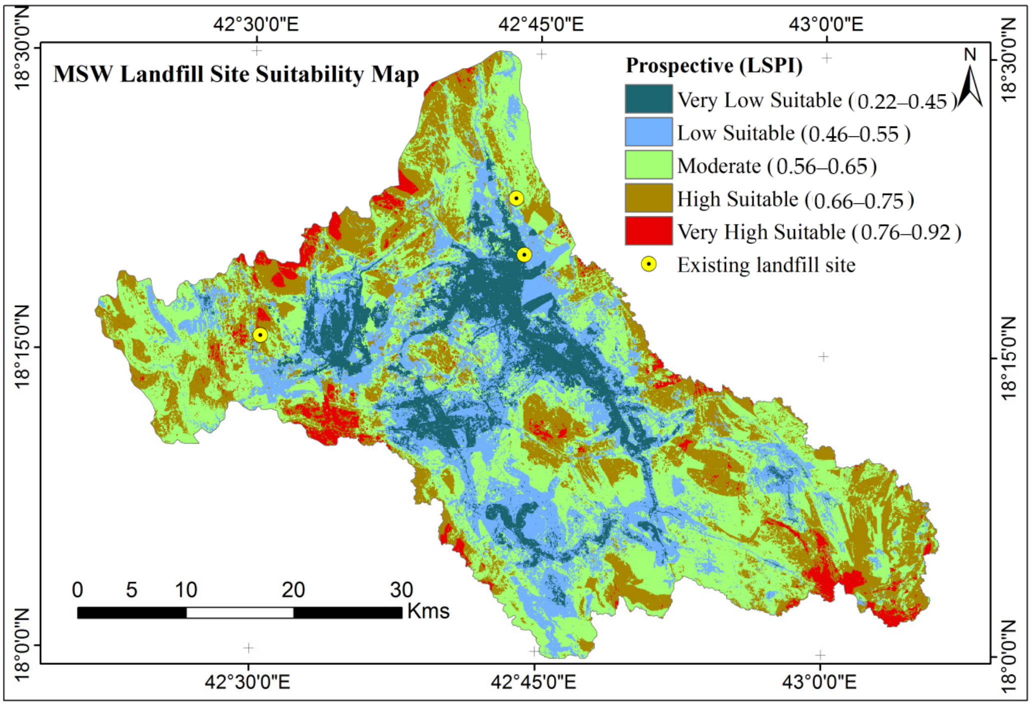

Figure 11. MSW landfill site suitable zone map.

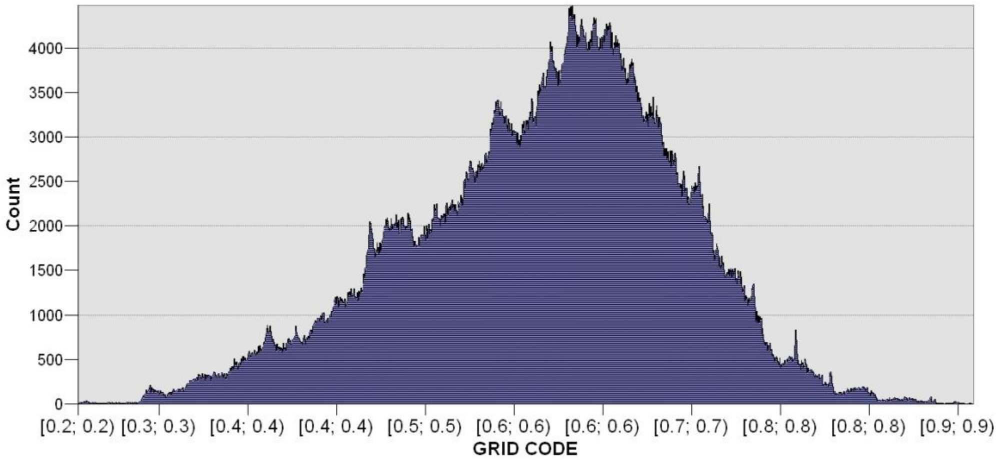

Figure 12. Histogram profile that shows the frequency of data distribution.

Table 8. Statistics of Integrated Categories of LSPZ with Existing MSW landfill site.

Sl. no	Zones of LSPZ	LSPI (Range)	Area	Area in %	Existing MSW Landfill Site
1	Very Low Suitable	0.22–0.45	202.81	11.44	1
2	Low Suitable	0.46–0.55	404.88	22.84	1
3	Moderate Suitable	0.56–0.65	676.08	38.14	0
4	High Suitable	0.66–0.75	423.85	23.91	1
5	Very High Suitable	0.76–0.92	65.03	3.67	0
	Total		1772.8	100.00	3

6. Discussion

Abha and Khamis-Mushyet city Municipality are the largest municipal authorities in the urban agglomeration of Aseer province. This increase in population growth, along with a rise in the living standards, has resulted in a huge rise in municipal solid waste generation. In addition, the ability to increase the buying capacity may lead to increased consumption, resulting in further waste generation. Hence, a high gross domestic product may be the reason for a society that encourages waste [29]. In 2018, the waste generation in Abha and Khamis-Mushyet accounted for 155 tons/yr. and 914 tons/yr., respectively. The dumping of such waste amount, the availability of suitable lands is needed to evaluate for the region/watershed sustainability.

The study attempts to integrate fuzzy set theory with Geospatial based analytical hierarchy approach: multi-criteria decision analysis (AHP-MCDM) that could be an effective tool for incorporating various features which affect the selection of landfill sites. The LSPM system focuses on structuring the process of decision-making. The author applies the fuzzy AHP method to determine the criteria weightings from the subjective method. The suggested framework determines that the fuzzy set theory integrated with the AHP-MCDA based on GIS can generate a high-reliability map for landfill site suitability area. For GIS-based MCDA, the fuzzy-AHP approach is promising as it fixes important limitations of traditional AHP. Initially, AHP has been utilized in a unilateral method to assign weights based on expert information to the parameters while permitting a specific level of subjectivity in the pairwise comparison matrix. Furthermore, a constrained scale of judgment, the rank reversal phenomenon, and the absence of transitivity, have recognized the inconsistency of the technique.

It is therefore important to address the AHP and its limitations in connection with this discussion part. Since the inception of AHP in the number of applications related to hydrogeology, environmental hazards, environmental planning, and ecological management, AHP became a very useful tool in the various field [112–125]. AHP has attained importance concerning the automatic calculation of priorities, interactive graphical user interfaces, and inconsistencies and a different approach to perform a sensitivity analysis, however, there is a lot of debate about the AHP methodology [123,126]. The phenomenon of rank reversal arises from the added/removed in the decision-making process of a new choice or the remove of an old choice. It leads to a change in ranking in past decisions. Initially, it was one of the major constraints of geocoded-based concepts that believed that the most relevant elements of decision-making are alternative and their utilities are based on the various parameters [127]. The problems with ranking persisted until Millet and Saaty [128] recommended the instances where ranking should be permitted to reverse. The instances demonstrated that AHP incorporates two possible methods for the process: ideal mode and distributive mode (allow for rank reversal). The AHP pairwise relationship uses a reliable approach to transform pairwise comparisons into a set of variables reflecting the relative priority of each criterion. While several other scales are addressed in the literature, none of them covers the previously described AHP issues fully. Saaty proposed a ratio scale used in the majority of applications [129]. In order to assess the criteria, the data uncertainty and the ambiguity of human choice create problems to provide correct numerical weights. In many of the cases, there is not a precise rating. Instead, intermediate ratings are used by the experts in order to give an idea of who best supports a particular area. Fuzzy-AHP contrasts with more adaptable to gain expert preferences in order to solve the problem of precision [130,131]. Each decision has a specific set of arrangement linked to a two-dimensional priority matrix in the fuzzy-AHP process (viz. criterion vs. criterion). In contrast, traditional AHP uses the pair-wise comparison of parameters in a top-down series and weight preference matrix as a result of a single similar priority matrix [129]. In view of the various consequences and interpretations of the evaluation criteria of the best arrangement, there is no valid justification for treating them all as equally important. In addition, fuzzy-AHP was used to resolve LSPM's categorical parameters (qualitative data) (e.g., LULC and geology) that are hard to explain in crisp values, hence improving the comprehensiveness and reasonability of the decision-making process [60]. With fuzzy sets, Fuzzy-AHP evaluates both priorities and data [129].

In this study, geospatial based fuzzy-AHP-MCDA was used to determine LSPM. This study explores the fact that the system uses artificial values derived from pairwise comparisons. However, Duru et al. [129] discussed different FAHP studies that did not have a matrix consistency problem, although the choices were inconsistent. The results showed that fuzzy set theory combined with AHP meets all the requirements. Our results indicated that the fuzzy set's integration with AHP is highly desirable in terms of effectiveness in alternatives and decision-making. The weighting and standardization/normalization criteria also take into account the uncertainties in the LSPM including both FMFs and Triangular Fuzzy Number (TFN) methods instead of crisp numbers to compare the relative significance between LSPM criteria. In addition, fuzzy logic is desirable due to easy to comprehend and implement in light of the fact that it is. Fuzzy logic could be used on data for any measurement scale, and the expert determines the weighting [60,62]. Nevertheless, using linguistic variables, the analysis provides a more realistic evaluation of landfill site suitability mapping. The fuzziness aspect of the data offers incorrect estimation that can be effectively resolved by using fuzzy-AHP weights [132,133].

Gorsevski et al. [7] and Demesouka et al. [134] have selected only geospatially dependent suitable landfill sites, this study has used an analysis of such suitable sites. Often, due to local environmental and public issues, GIS and a multi-criteria-based suitability analysis have identified sites that may not be suitable for landfill [48]. The present study, therefore, performed a post-suitability field investigation to consider the final landfill sites by taking into account local acceptance and environmental concerns. What is more important in this study was the selection of variables that identified people's awareness and perception of the location of municipal landfill sites. By using a weighted linear combination and overlay analysis, the approach used encourages site suitability, which was deemed desirable because assigning weight to the criterion using statistical techniques and matrix helps to minimize human bias [12,48,135]. The weighted overly based suitable landfill potential sites can be considered for new and back-up municipal waste landfill sites for the future, also in this study, the proposed GIS-based Fuzzy-AHP models make the application more realistic and reliable.

7. Conclusions

In the last few decades, Aseer region's urban and semi-urban population, especially in Abha and Khamis-Mushyet, has increased dramatically. The waste is disposed of in an inappropriate location affecting the climate, water supply and the esthetics of the environment. Selection of landfill sites is significant, as it has a negative impact on the micro-climate of the region. Random and non-scientific selection of landfill sites may have a negative impact on the climate, people and surrounding aquatic resources, including groundwater. It has been argued that knowledge of hydrology, land use/land cover, geology, and landfill site understanding is most relevant to the selection of suitable landfill sites. A review of past studies has shown that there is no significant study of the optimized location of the municipal solid waste landfill in Abha-Khamis-Mushyet that has been performed.

The study provides an integrated framework with a focus on structuring the decision-making process for the landfill suitability site map. This could be determined by the use of proper data collection, criterion weighting and normalization. In order to understand the procedures that affect the suitability of landfill sites, the integrated GIS-based fuzzy-AHP-MCDA method was implemented to appropriate landfill site areas. The suggested method determines that a high-reliability landfill site potential map can be generated by the fuzzy set theory coupled with GIS-based AHP-MCDA. According to the results of the analysis, it can be mentioned that the inclusion of fuzzy sets with AHP gives high flexibility in preferences and decision-making in both criteria weighting and normalization. The weighting and standardization/normalization criteria also take into account the uncertainties in the LSPM including both FMFs and Triangular Fuzzy Number (TFN) methods instead of crisp numbers to compare the relative significance between LSPM criteria. In addition, fuzzy logic is desirable due to easy to comprehend and implement in light of the fact that it is.

Accordingly, this study explores a simplified system of multi-criteria decision making (MCDM) and a fuzzy membership in the GIS setting to assess the best landfill sites for

Abha-Khamis-Mushyet located in Aseer region. After the extensive literature review and expert opinion, 10 themes were selected for this research such as drainage density, LULC, slope, elevation, lineament density, NDVI, rainfall, distance from the airport, distance from road and geology. These themes have been developed through RS (remote sensing) and conventional data. Subsequently, potential landfill sites were identified and divided into five classes: namely very low suitable (fuzzy value 0.20–0.45), low suitable (0.46–0.55), moderately suitable (0.56–0.65), high suitable (0.66–0.75), and very high suitable (0.76–0.92). As per the statistical analysis, 23.91% and 3.67% of the total area were under very good and good landfill site suitable zone, while 38.14% and 22.84% accounted to the moderate and poor suitable zone, respectively. As a quality-based site, the existing two landfill sites were located over a very low suitable and low suitable potential area while one landfill site was located over the high suitable potential area. The spatial variance of high and very high potential landfill site zones found in the north-eastern, east-central, and south-eastern parts of the watershed. The sensitivity analysis was performed to know the effectiveness of each parameter. The drainage density, LULC, geology, and Distance to road and slope play a significant role in the LSPI assessment (37.88%, 18.78%, 14.86%, and 7.21%, respectively). This may be because of the high theoretical weight of all of these parameters. The effective weights for each theme, however, are slightly different from the theoretical weight assigned to the suitability zone of the landfill site.

This study provides a scientific basis for the study area using multi-criteria-based suitability analysis. The best and common approach to determine the appropriate municipal landfill sites by using the Fuzzy AHP and weighted overlay. The applied technique can adjust the level of influence and the weight-based level of risk in the decision-making processes in order to optimize their suitability. This technique was applied to determine areas of potential and environmental risk posed by municipal waste disposal. In order to ensure environmental protection and local esthetic value, public awareness and health, more specific and interconnected parameters in the study region were considered as geo-environmental factors for sites located at the site. The present study provides a valuable approach to understanding the suitability of landfill sites in the studied watershed that can be used by hydrogeologists, engineers, regional planners, and decision-makers as the initial basis for reconsidering whether new urban waste disposal sites are being built or not.

In the present study focused on the significance of GIS techniques in the selection and location of appropriate sites for landfill. In terms of the degree of suitability for landfill sites, this analysis involved the assessment of wide spatial and aspatial information input data and retrieved output. This study demonstrates that it is feasible to use the suitability analysis method to a wide range of real-world issues and environments, not only on landfills and waste management issues but also in a wide range of other situations.

Finally, it is recommended that in order to choose the most appropriate MSW sites for landfill construction, the findings of the study should be compared with field studies. Some supplemental field studies would need to be carried out on the sites including field investigations of geological and geotechnical characteristics, such as determining appropriate borrow materials as liner of the landfill, evaluating permeability of units by field experiment, hydrogeological analyses towards the protection of surface water as well as groundwater (including leachates), property rights, analysis of discontinuities characteristics at the chosen landfill site (e.g., dip direction, aperture, and filing of joint sets, etc.), comprehensive waste inventory, questionnaire investigations to assess consumer awareness and public acceptance, and assessment of construction suitability.

Funding: Funding for this research was given under award numbers R.G.P2/92/41 by the Deanship of Scientific Research; King Khalid University, Ministry of Education, Kingdom of Saudi Arabia.

Institutional Review Board Statement: Not applicable.

Informed Consent Statement: Not applicable.

Data Availability Statement: Not applicable.

Acknowledgments: Author thankfully acknowledge the Deanship of Scientific Research for proving administrative and financial supports and NASAUSGS personnel at the land DAAC provided the latest satellite image was greatly appreciated.

Conflicts of Interest: The authors declare no conflict of interest.

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