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Multi-criteria spatial analysis for locating waste landfill with Boolean and weighted approach in Mazandaran province, Iran

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ARTICLE INFO	ABSTRACT

The selection of landfill sites and the utilization of modern sanitary burial methods must consider the environmental regulations of each country. Given the impacts that landfill sites have on ecosystems and their surrounding environments, it is essential to ensure that the location chosen for landfill minimizes destructive effects and adverse impacts on its surroundings. The objective of the present study was to identify suitable locations for the disposal of industrial waste in Mazandaran Province. Iran. In selecting waste disposal sites, all environmental, geological, hydrological, topographic, physiographic, climatic, soil science criteria, protected areas, buffer zones for oil, water and power transmission lines, access roads, population areas, and other criteria stipulated in legal regulations were considered. The spatial analysis of the results of this study showed that 22.6% of the area of Mazandaran Province conflicts with 15 environmental criteria. The results from overlaying the prepared informational layers, while adhering to each technical standard for establishing an industrial and special waste storage center using the Boolean method, indicated that none of the areas in Mazandaran Province meet the current technical standards for establishing a special waste storage center, and it is not feasible to establish such a center in Mazandaran Province.

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1. Introduction

Industrial growth and the development of diverse products, coupled with increased consumerism among citizens, have significantly contributed to the rise in urban and industrial waste generation (Abdoli et al., 2009). In many cases, improper handling and disposal of industrial waste, which may contain hazardous materials, pose serious challenges to both human health and the environment. Effective control and management of industrial waste are crucial for environmental health and the sustainable management of natural resources. With the rapid industrial development of urban areas, the management, collection, transportation, disposal, and recycling of industrial and quasi-household waste have become increasingly important (EPA, 2004; Abdoli et al., 2010). Given the significant environmental impacts of landfill

sites on ecosystems and their surrounding areas, it is essential to ensure that landfill locations are selected in ways that minimize destructive effects and adverse impacts on nearby environments (Jalilian et al., 2022). Consequently, effective management and strategic planning for organizing industrial waste are imperative. Poor site selection for waste disposal can result in groundwater contamination, air pollution, disease outbreaks, and other harmful consequences for surrounding areas. The selection of industrial landfill sites is a critical step in waste management, and given the destructive environmental, economic, and ecological effects of waste, the process must be conducted carefully and based on scientific methodologies.

Rezaeisabzevar et al. (2020) identified groundwater depth, proximity to the water table, elevation, land slope, soil

permeability, flood resistance, lithology, protected areas, wind direction, proximity to roads, railways, construction materials, pipelines, and airports as the most critical factors influencing landfill site selection. Shayan et al. (2018) employed a fuzzy logic method to optimize landfill site selection for rural waste in Zarindasht County. Their findings demonstrated that the most suitable landfill sites are near transportation routes, while the least suitable ones are close to human settlements. Of the 4,626 km² area of Zarindasht County, 3.83% was found to be completely suitable for waste disposal, 48.98% suitable, 35.2% moderately suitable, 9.03% unsuitable, and 2.33% completely unsuitable.

Moradi and Mousavi (2019) focused on rural waste landfill site selection in the Soumaeh South district of Urmia County. Using a Multi-Criteria Evaluation (MCE) approach integrated with Geographic Information Systems (GIS), appropriate landfill sites were identified through a multi-step process. This involved preparing constraint maps, geomorphology, climate, water resources, socio-economic factors, environmental considerations, and geological hazards. The overlay of constraints and location factors revealed that only about 6% of the district's area was suitable for landfill sites. Abasnezhad et al. (2017) conducted landfill site selection in Maku City using both fuzzy logic and Boolean methods. They utilized multiple layers, including topographic maps, slope maps, groundwater maps, road networks, urban and rural area maps, and land use maps. The results indicated that the optimal site is located in the northeastern part of Maku County at an elevation between 700 to 900 meters. The estimated area using the Boolean method was 24,528 m², while the fuzzy method calculated an area of 14,957 m².

Madadi et al. (2013) conducted a study aimed at identifying suitable landfill sites in Ardabil County and comparing different methods, including Weighted Overlay, Analytic Hierarchy Process (AHP), Fuzzy Logic, and Boolean Logic, to determine the most effective approach for selecting solid waste landfill locations in Ardabil City. The results highlighted the effective application of AHP, Weighted Overlay, and Fuzzy Logic, with AHP being the most suitable method for landfill site selection in the region. Jalilian et al. (2021) utilized the Stepwise Weight Assessment Ratio Analysis (SWARA) method, Geographic Information Systems (GIS), and the COPRAS method to identify appropriate landfill locations for municipal solid waste in Kermanshah City. The SWARA results indicated that water resources, soil, and distance from agricultural lands were the most critical criteria, with final weights of 0.3, 0.202, and 0.119, respectively. Conversely, slope, distance from power transmission lines, and proximity to faults were the least significant criteria, with final weights of 0.02, 0.015, and 0.015, respectively. Ahmadi and Sobhanardakani (2022) employed ArcGIS software to locate solid waste landfill sites in Songhor County. Their findings revealed that 17.8% and 45% of the study area were deemed unsuitable and inapplicable for urban waste disposal, respectively.

Despite the abundance of natural resources and the high environmental sensitivity in Mazandaran Province, no studies have been conducted on the siting of special waste disposal centers in the region. Due to the inherent complexities of the process, the use of Fuzzy Logic is recommended over Boolean Logic, as Fuzzy Logic can provide more accurate results. The present study aims to identify suitable landfill sites for industrial waste in Mazandaran Province. This research gap persists despite the existence of mandatory technical guidelines for designing special waste landfill sites approved by the Environmental Protection Organization.

2. Materials and Methods
2.1 Study area

The study area for this research is Mazandaran Province (Fig. 1), located between 35°47′ and 36°35′ north latitude and 50°00′ and 54°10′ east longitude from the Greenwich meridian. According to the latest administrative divisions, Mazandaran Province comprises 22 counties, which are naturally divided into coastal plains, lowlands, and mountainous areas.
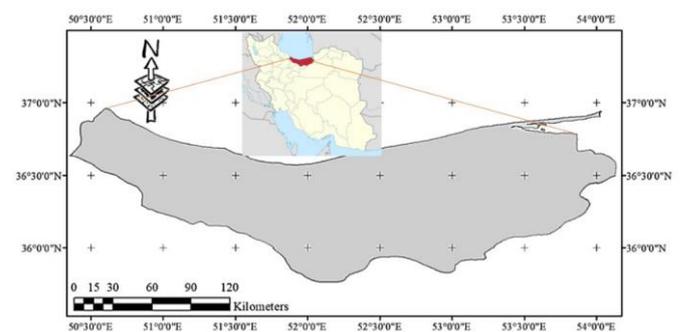

Fig. 1 The scope of the study (Mazandaran province)

The Alborz Mountain range acts as a towering barrier, enclosing the coastal strip and lowlands along the Caspian Sea. Mazandaran Province covers an area of approximately 23,756.4 km², accounting for 1.46% of the country's total area. It is bordered to the north by the Caspian Sea, to the south by Tehran and Semnan provinces, to the west by Gilan Province, and to the east by Golestan Province. The main ridge of the Alborz Mountain range stretches across southern Mazandaran, acting as a barrier that prevents the Caspian Sea's moisture from reaching central Iran. The resulting accumulation of moisture along the northern slopes of the Alborz causes heavy rainfall. Due to factors such as wind patterns, topography, proximity to the sea, and latitude, two distinct climates are observed in the province: a temperate, humid, and lowland climate in the western plains and some central regions, and a mountainous climate in the highland areas (Anonymous, 2022).

2.2. Landfill site selection algorithm

The site selection process within a GIS environment involves several pre-processing and processing steps. Initially, the criteria and constraints were identified and prepared as map layers, which were then processed within the GIS environment. This study utilized maps with a scale of 1:25,000. Since the site selection process is implemented in a raster-based model, the chosen software must support raster modeling and decision-making rules. Given GIS's extensive capabilities in this regard and its raster-based foundation, it was selected as the primary software for the operations. The Analytic Hierarchy Process (AHP) is one of the most

comprehensive methods designed for multi-criteria decision-making. It is used to make decisions and select an option among multiple alternatives based on criteria chosen by the decision-maker (Melon et al., 2008). AHP is a widely used method for multi-criteria decision-making, particularly for assigning weights to criteria and sub-criteria. The core of AHP is pairwise comparisons between options and decision-making criteria, enabling managers to evaluate various scenarios effectively.

In pairwise comparisons, respondents evaluate only two factors relative to each other without considering other factors, providing valuable insights into the issue and making the decision-making process more logical. In AHP, calculations are carried out using the expert choice software. The AHP decision-making process generally involves defining a hierarchical structure, calculating the relative weights of criteria, determining the consistency ratio, extracting priorities from pairwise comparison tables, and selecting the best option. The primary condition for accepting pairwise comparisons is that they must be consistent. To ensure this, the consistency ratio (CR) of each matrix is calculated. The CR indicates the reliability of the derived priorities. If the CR is less than 0.1, the comparisons are considered consistent; otherwise, the comparisons must be revised (Melon et al., 2008).

2.3 Fuzzy and boolean logic

Before beginning the site selection process and integrating maps, all utilized layers must be standardized based on the provided criteria values. This means that all layers are converted to a uniform scale, enabling their integration using decision-making rules. For this purpose, fuzzy logic was employed (Pourkhosravani et al., 2017). In the fuzzy logic method, each point on the target land is assigned a membership value using different thresholds and fuzzy membership functions. This value indicates its suitability for solid waste disposal, with higher membership values representing higher suitability and lower values indicating lower suitability (Karimzadeh Motlagh and Sayadi, 2015). Since computer color spectra are limited to 256 shades, a scale of 0–255 was used instead of the typical 0–1 scale. In this range, values closer to 255 indicate greater suitability. This process was carried out in ArcGIS software based on site selection criteria and after performing the necessary tests for all available functions.

In this study, fuzzy and Boolean overlay methods were used to optimally locate industrial waste disposal sites in Mazandaran Province. First, various technical criteria essential for landfill site selection were identified and mapped. Then, using the Boolean overlay method, unsuitable areas were completely eliminated, leaving only the potentially suitable regions. To further evaluate the remaining areas with greater precision, the fuzzy overlay method was applied. This approach allows each area to be assessed relatively and with varying degrees of suitability based on different criteria. Initially, appropriate membership functions were defined for each criterion, and fuzzy maps were generated. Next, fuzzy operations, such as AND and OR, were used to combine the maps and create a final map indicating the most suitable locations for waste disposal with higher accuracy. This process helped to precisely identify areas with the highest potential (Madadi et al., 2013).

Various criteria must be weighted according to their relative importance. However, given the environmental criteria, Boolean logic was applied in the site selection analysis for Mazandaran Province. Accordingly, all analyses were conducted in GIS software using appropriate maps prepared based on the criteria and technical conditions. This study was carried out using an analytical-descriptive approach. After collecting and verifying the data, the maps were thoroughly evaluated and reviewed within the GIS environment. Initial processing and alignment of overlays and coordinate systems were performed. Once fully aligned, the coordinate system was set to WGS 1984 UTM Zone 39N. The study area and dimensions were finalized using a window with specific dimensions and a pixel size of 450 m × 450 m. It should be noted that all technical standards were applied within the designated area, adhering to the appropriate scale. The most precise maps were the topographic and DEM maps with spatial resolutions of 30 m and elevation intervals of 10 m, which were used to derive slope and elevation range maps. The remaining maps were scaled to 1:50,000 and 1:20,000.

In this study, addressing the challenges of special and industrial waste disposal in Mazandaran Province was examined and evaluated by integrating modern spatial information methods with weighted approaches based on previous studies in the GIS framework. The steps taken are summarized as follows:

- Preparation and determination of evaluation criteria for special waste disposal based on the technical regulations of the Environmental Protection Organization and national laws;
- Compilation and integration of all thematic maps with the highest available precision, including the digital elevation model (DEM) of Mazandaran Province with a spatial resolution of 10 m, and other maps scaled at 1:25,000, obtained from the National Cartographic Organization and the Management and Planning Organization, into a central database;
- Conversion of criteria maps to raster format for applying final weights;
- Utilization of advanced and modern fuzzy standardization methods based on a scale of 0 to 255, where 0 represents completely restricted areas, and 255 indicates areas that fully meet the environmental criteria for special industrial waste disposal;
- Generation of a spatial suitability map for waste disposal by applying weighting factors.

3. Results and Discussion

3.1 Conflicts between current waste disposal sites and site selection criteria for waste disposal centers

A significant volume of waste produced in Mazandaran Province is improperly and unsafely stored or buried in primitive conditions near rivers, coastal areas, forests, and pastures. There are currently 27 municipal waste disposal or landfill sites in Mazandaran Province. These sites blatantly violate the regulations and guidelines of the Environmental Protection Organization regarding site selection and fail to meet the legal distance

requirements from designated land uses. Using spatial analysis within the Geographic Information System (GIS), the final processing of special waste disposal site selection revealed that each of the current municipal waste landfill sites in Mazandaran Province conflicted with several of the 18 criterion maps used in this study, as identified through the spatial violation maps of national environmental regulations.

Table 1 The selected final weight is standardized according to percentage and weight factor based on previous studies and the opinion of environmental experts to choose the optimal place for waste disposal

Rank	The criterion of the research	Weighting factor	Percent (%)
1	City	0.1830	18.3
2	Village	0.1600	16.0
3	Dams	0.1040	10.4
4	Water Well	0.0850	8.50
5	Protected areas	0.0670	6.70
6	Main and secondary waterways	0.0620	6.20
7	Wetlands	0.0500	5.00
8	Slope	0.0480	4.80
9	Height	0.0430	4.30
10	Beach	0.0410	4.10
11	Land use	0.0400	4.00
12	Floodwater	0.0330	3.30
13	Airport	0.0300	3.00
14	Active and passive faults	0.0250	2.50
15	Main and secondary roads; and railway lines	0.0170	1.70
16	Mines	0.0050	0.50
17	Electricity, gas and oil transmission lines	0.0040	0.40
18	Soil	0.0010	0.10

After consulting technical experts from the Department of Environmental Protection, specialists, university faculty members, and considering the unique conditions of Mazandaran Province, the weights for each criterion were determined as shown in Table 1. These weights were applied to the criterion maps during the weighted analysis process.

3.2 Criterion maps

After determining the final weights, the selected criterion maps for spatial analysis and optimal site selection for special waste disposal in Mazandaran Province were prepared using buffer zones and the fuzzy logic method. The GIS-based site selection analysis incorporated multiple environmental, social, and climatic factors. To simplify the analysis, the 18 factors used in this study were named and presented in Table 1 as raster maps.

One of the key factors in site selection for waste disposal, from the perspective of social conflict, is applying distance restrictions and buffer zones around urban areas. Due to the high population density and proximity of numerous cities and villages, Mazandaran Province has unique conditions regarding distance from urban areas for waste disposal. To minimize adverse impacts on the human environment, many studies recommend a buffer zone exceeding 3000 m (Jalilian et al., 2022). In this study, however, the buffer zone for waste disposal site selection was set at 1000 m, based on existing technical regulations. After acquiring the maps, initial processing was performed on the polygon vector maps, and a 1000 m buffer was applied around the cities and towns in Mazandaran Province. Following the necessary transformations, the final map, as shown in Fig. 2, was extracted and used in the final overlay analysis. It should be noted that, as depicted in Fig. 2, this restriction was applied

across all urban and rural populated areas in Mazandaran Province. Zamorano et al. (2008) demonstrated that the distance from residential areas holds the highest weight and significance in landfill site selection.
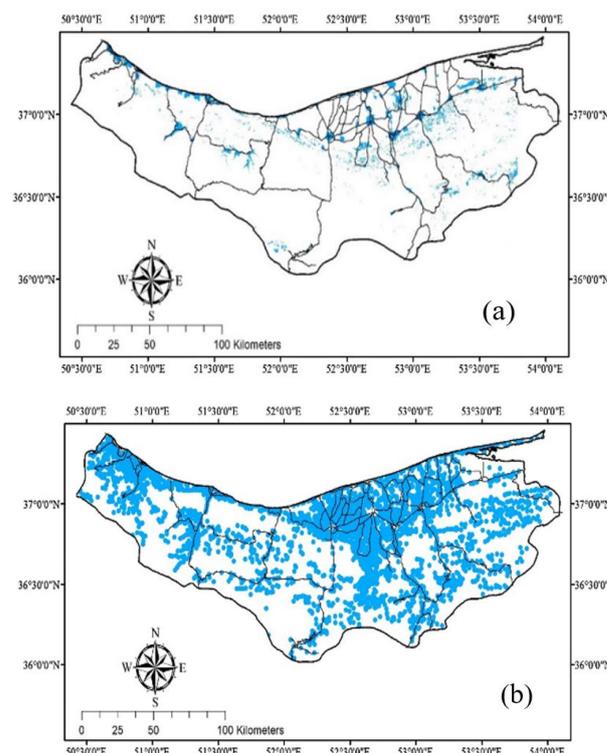

Fig. 2 The population zones of a) urban areas and b) rural areas in Mazandaran Province are within a 1000 m buffer zone, in accordance with the mandatory technical requirements for waste disposal

One of the requirements outlined in the technical guidelines is the establishment of buffer zones around water storage dams and the prohibition of waste disposal or burial in the main and tributary branches of dry and permanent rivers located upstream of these dams. In this study, point data regarding operational, under-construction, or planned dams in Mazandaran Province were collected, and a 1000 m buffer zone was created, along with a buffer for upstream branches. The output, indicating unsuitable areas for waste disposal, is presented in Fig. 3a. More than 70% of the province's area falls under this restrictive condition. According to the reviewed sources, this factor ranks fourth in importance and is a significant environmental criterion influencing the selection of appropriate waste disposal sites.

Another critical restrictive factor, both environmentally and socially, in Mazandaran Province is the buffer zone around drilled water wells. In addition to authorized operational wells, many sources of drinking water, agricultural irrigation, and industrial activities in Mazandaran rely on unauthorized wells. Regardless of technical discussions, the health and environmental sustainability of this major water source in Mazandaran depend heavily on its microbial and chemical safety. Based on various sources, water wells rank as the seventh most important environmental factor among the criteria for selecting waste disposal sites. In this study, data for over 2500 authorized wells in Mazandaran Province were analyzed, and a 400 m buffer was applied according to technical regulations. Consequently, more than 17% of the province's area was deemed unsuitable for waste disposal based on these technical conditions. Most of these authorized wells are located on aquifers, placing this factor fourth in terms of unsuitable area coverage for waste disposal. Undoubtedly, applying restrictions to unauthorized wells would further expand the restricted area (Fig. 3b).
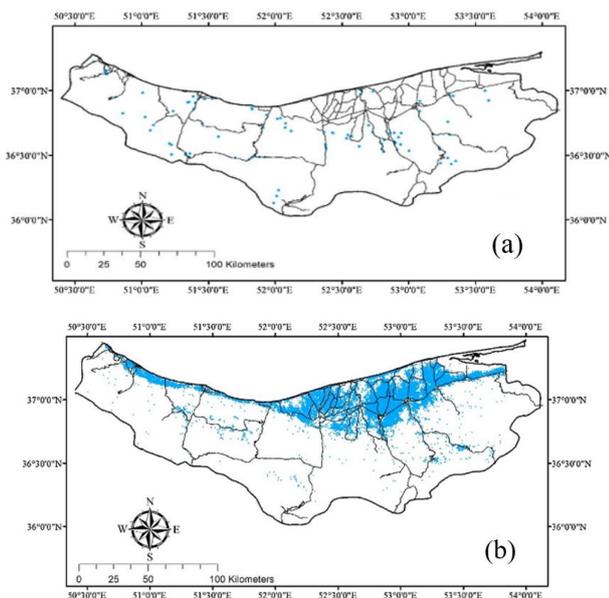

(a)

(b)

Fig. 3 a) The scope of all the dams in operation and under study in Mazandaran province, including the 1000 m buffer of the hydraulic structure and the areas related to the main and dry branches of the river leading to the dams and b) The range of permitted water wells in operation in Mazandaran province with a buffer of 400 m

Considering the four protected areas under the management of the Environmental Protection Organization in Mazandaran Province, a review of environmental sources ranked these zones as the fifth most important factor. Spatial analysis of the protected areas indicated that approximately 25% of the province's area falls under this environmental factor. In terms of unsuitable areas for waste disposal, this factor ranks fifth in terms of coverage (Fig. 4a).

Mazandaran Province, with its numerous main and tributary rivers, ranks fifth in terms of unsuitable areas for waste disposal due to the enforcement of a 1000 m buffer zone, as required by technical regulations. To prevent interference and mitigate the consequences of waste infiltration into the province's surface waters, maintaining a proper distance from rivers is critical. This environmental factor accounts for approximately 75% of the province's area (Fig. 4b). Gorsevski et al. (2012) demonstrated that proximity to waterways significantly increases the likelihood of surface water contamination from waste disposal sites.
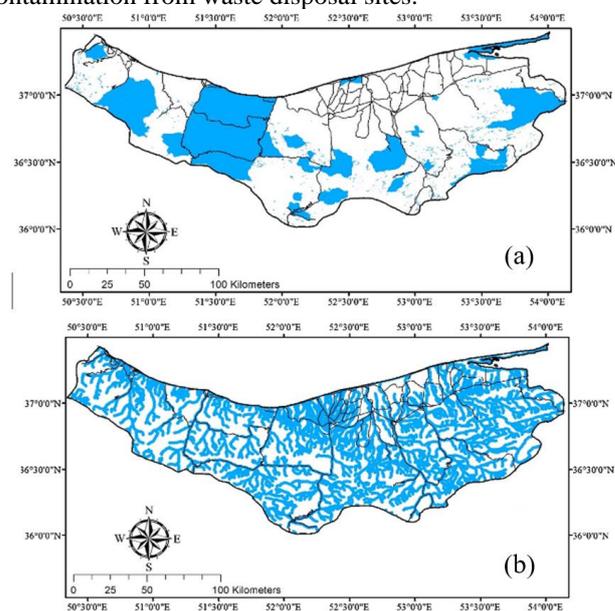

(a)

(b)

Fig. 4 a) The boundaries of the four areas under the supervision of the Environmental Protection Organization of Mazandaran province with a buffer of 1000 m and b) The range of rivers in Mazandaran province with a buffer of 1000 m

Another environmentally restrictive factor in determining suitable waste disposal sites is the presence of water bodies such as wetlands and lakes in the province. These areas are recognized as the seventh most important factor in various sources, and in terms of area, spatial analysis for Mazandaran Province places them at rank 20, accounting for 1.2% of the province's area. According to technical guidelines (Jalilian et al., 2022), waste disposal in aquifer zones is prohibited. This environmental factor ranks as the seventh most significant among the 18 factors considered in this study based on a review of credible sources. Spatial analysis of key aquifer maps in Mazandaran Province shows that, in terms of unsuitable areas for waste disposal, aquifers rank 14th, covering approximately 16% of the province's area. Due to its humid climate, abundant rainfall, high density of surface water flow, and permanent rivers, Mazandaran Province boasts rich

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vegetation and fertile alluvial plains formed between the sea and the mountains, resulting in suitable groundwater reservoirs. The aquifers formed in the plains and coastal alluvial zones generally feature high-quality water. The spatial analysis map of geohydrology, shown in Fig. 5a, highlights the extensive coverage of this critical restrictive factor, particularly in the valuable and resource-rich plains extending from the eastern to the western coastal areas of Mazandaran Province.

Another critical factor highlighted in many sources and environmental regulations is the restriction on slope and elevation for waste disposal sites. Numerous scientific studies (Jalilian et al., 2022) consider land slopes exceeding 10% and elevations above 2500 m unsuitable for waste disposal. The terrain, infiltration control, and potential leachate flow in waste disposal, considering topographic conditions and ease of access to the site, are crucial factors. Therefore, determining an appropriate slope for waste disposal ranks as the eighth most important criterion, based on previous studies and technical guidelines.

Although sloped areas have historically seen less human encroachment, advancements in technology have led to increasing human activities on mountainous slopes, such as road construction, terraced agriculture, power transmission towers, and water supply or oil projects. These activities also affect waste disposal sites and related infrastructure, especially in areas with steep slopes and unstable terrain. Steep slopes, due to initial processes, gravitational forces, and surface runoff, are highly dynamic and prone to landslides and subsurface leachate flow.
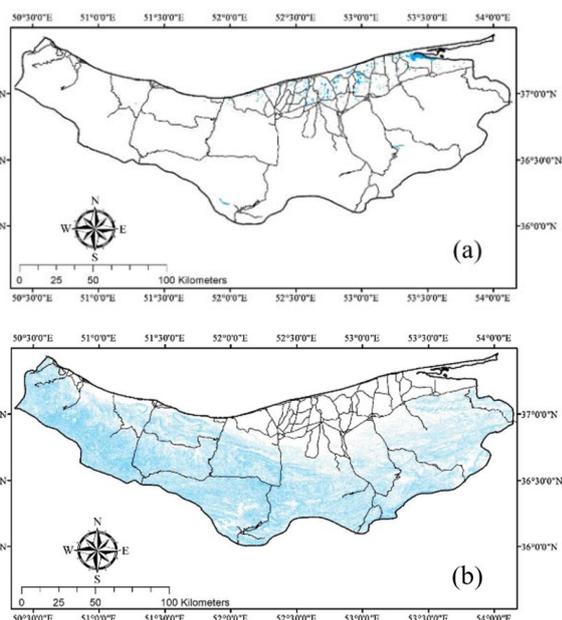

Fig. 5 (a) The range of water areas of wetlands and natural and artificial lakes of Mazandaran province with a buffer of 1000 m and (b) The suitable slope range for special waste disposal in Mazandaran province includes a slope of less than 10%

The findings of this section align with those of Emadodin et al. (2020). Ultimately, the role of slope in locating waste disposal centers, particularly facilities and storage areas, is highly significant. Most sources consider slopes exceeding 10%

entirely unsuitable for waste disposal. Applying the 10% slope restriction, unsuitable areas were identified and are presented in Fig. 5-b. More than 65% of the province's area is classified as unsuitable due to slope-related environmental factors. Spatial analysis of the slope and digital elevation models (DEM) places these factors in the eighth and ninth ranks in terms of importance.

Land use is a critical environmental factor influencing the selection of waste disposal sites. The land use in a given area should not interfere with or hinder other activities. In Mazandaran Province, valuable land uses such as fertile agricultural lands, forests, pastures, and wetlands are recognized as vital restrictive factors for locating waste disposal centers. According to expert opinions and the reviewed sources, land use maps rank as the 11th most important environmental factor. The spatial analysis output for land use in Mazandaran Province indicates that prime agricultural areas, including rainfed and irrigated farming lands, orchards, forests, pastures, and ecologically beneficial vegetation, are the top-ranked categories in terms of restrictions and unsuitable areas for waste disposal. Quantitative results from the spatial analysis of land use maps reveal that over 95% of the province's area is classified as valuable and unsuitable for special waste disposal from this perspective (Fig. 6a). Thus, Mazandaran's water, air, and vegetation resources are highly significant from an environmental standpoint. Quantitative analysis indicates that approximately 2,280,000 hectares of land are unsuitable for various types of waste disposal. Allen et al. (2003) reported a minimum required distance of 3000 m between landfills and agricultural lands. Field survey results further confirmed that the proposed landfill sites maintained a distance of more than 3000 m from agricultural lands.
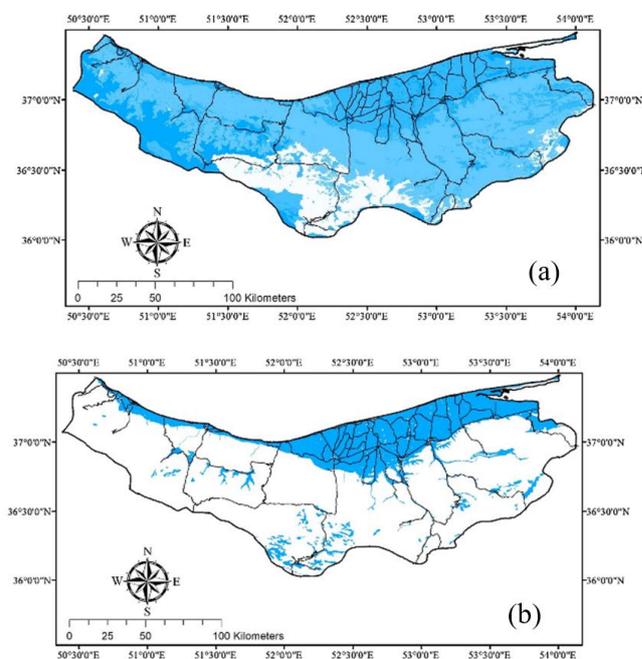

Fig. 6 a) The range of vegetation in Mazandaran province includes gardens, rainfed and irrigated agriculture, forests and pastures with a buffer of 1000 m and b) Flood area of Mazandaran province with 1000 m barrier

Based on a review of previous studies, flood-prone areas with a 100-year return period rank 12th among the criteria for selecting waste disposal sites. As previously mentioned, Mazandaran Province is one of the most water-abundant regions in the country, featuring numerous surface streams and permanent rivers. The density of the drainage network is a valuable indicator for assessing the flood potential of watersheds. Large watersheds ranked 4th, 5th, and 6th within Mazandaran Province, due to their extensive size and dense drainage networks, are characterized by relatively stable and established riverbeds. The presence of abundant natural drainage channels and large riverbeds significantly reduces the potential impact of flooding. Floodplain areas with a 100-year return period, combined with a 1000 m buffer as mandated by technical regulations, designate unsuitable areas for waste disposal, as shown in Fig. 6b. The results indicate that the flood hazard environmental constraint ranks 12th, covering approximately 9% of Mazandaran Province's total area. These findings align with those of Pouramraei et al. (2020), who used a weighted linear combination model in ArcGIS to locate municipal solid waste disposal sites in Kuhdasht. Their results showed that only a limited portion of the area (19%) was suitable for waste disposal.

3.3 Final maps for locating special and industrial waste disposal centers

Fig. 7 illustrates the results of overlaying the prepared informational layers while adhering to each of the technical regulations for establishing special and industrial waste disposal centers, using the Boolean method. As shown in this figure, it is evident that none of the areas within Mazandaran Province meet the current technical criteria for establishing a special waste disposal center. Consequently, constructing such a facility in Mazandaran Province is not feasible.

The map of optimal waste disposal areas based on weighted importance is presented in Fig. 8. It is important to note that, based on the weighted method applied in the final map, no area with a value of 255, indicating full compliance with all legal regulations, was identified. The same result was observed using the Boolean method. Fig. 8 illustrates the results of overlaying the prepared informational layers while adhering to each of the technical regulations for establishing special and industrial waste disposal centers. According to the findings, none of the areas within Mazandaran Province comply with the current technical criteria for constructing industrial and special waste disposal centers. Therefore, establishing such facilities in Mazandaran Province is not feasible. Jalilian et al. (2022) demonstrated that out of 36 sites evaluated, the Shahvali site met environmental parameters, including a distance greater than 3000 m from surface and groundwater resources and residential areas, as well as a slope of less than 10%.

Fig. 7 The final map resulting from the location of the special waste disposal center using the Boolean method based on the standards, criteria and environmental technical conditions applicable in the design
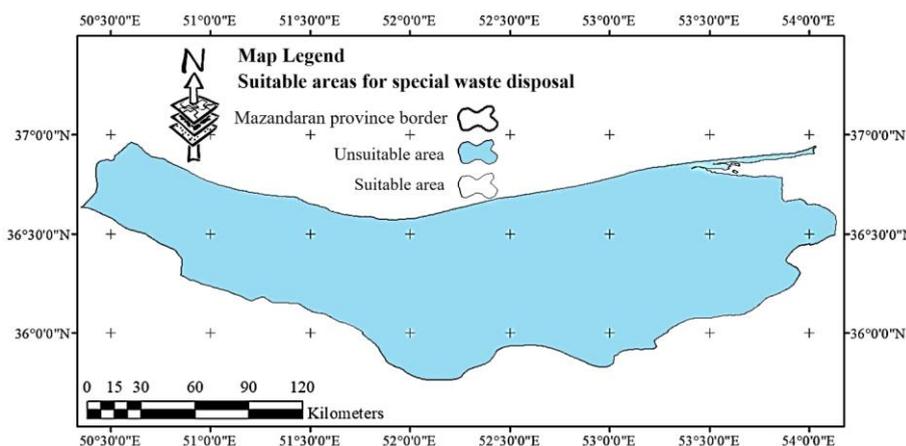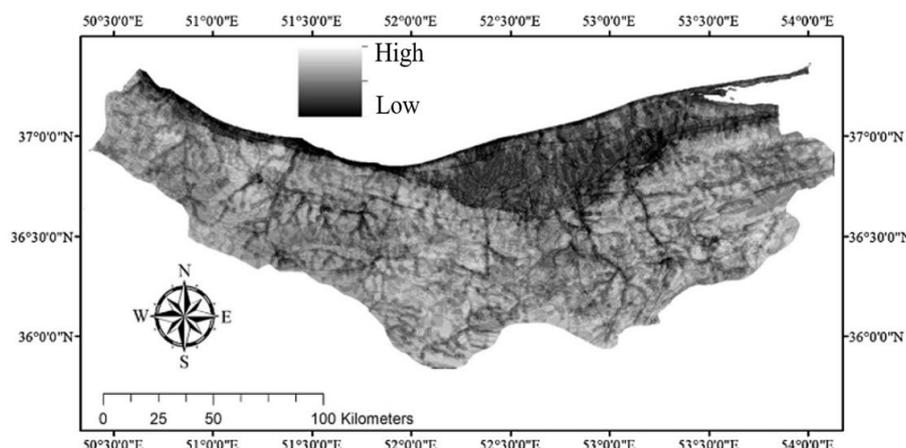

Fig. 8 Merit map of a suitable place for disposal of special waste in Mazandaran province (points with darker colors are completely inappropriate and lighter points are relatively suitable-contrary to fewer laws)

The values in Table 2 are derived from the sum of environmental criterion violations. A value of 18 indicates that the identified areas are entirely incompatible with the technical site selection guidelines for special industrial waste disposal centers. (Notably, the results suggest that no suitable location (depicted in white) exists within Mazandaran Province's boundaries, given the environmental, social, and climatic constraints.) The lower the score, the more unsuitable the area is deemed for constructing a waste disposal center according to fewer technical regulations. In other words, lighter-colored areas do not imply suitability for waste disposal center site selection. For instance, areas adjacent to wetlands, urban or rural areas, or protected zones might only violate one technical rule, but in practice, constructing such a center in these locations is infeasible. These areas are thus recognized as fundamental and non-negotiable constraints. The site selection process for waste disposal areas in Mazandaran Province, based on Boolean logic and mandatory guidelines, underscores the sensitivity of the region's conditions. It is worth mentioning that the output maps, which use zoning based on waste disposal priorities under technical conditions and fewer constraints (represented by lighter gray areas with higher scores ranging from 0 to 255), could be further examined if certain limitations are waived. Therefore, multi-criteria decision-making methods such as weighting and hierarchical approaches in GIS cannot identify a location that fully complies with all technical guidelines.

The dark and black areas on the map in Fig. 8 represent critical zones for waste disposal, as they are deemed unsuitable due to a higher number of limiting factors. On average, 12 environmental constraints make these locations inappropriate for waste disposal or burial. These zones are characterized by highly specific environmental, social, and climatic conditions and have received very low suitability scores for waste disposal. This conclusion is supported by the frequency analysis of restricted area violations presented in Table 2. It is worth noting that the significance of certain environmental factors, such as being located within the four protected environmental zones, can alone be a decisive reason for the unsuitability of a waste disposal site. In conclusion, the findings of this study indicate that Mazandaran Province is in an extremely sensitive climatic, environmental, and social situation. Considering the unique conditions, existing laws, and higher-level policies aimed at preserving resources and reducing social conflicts especially given the high population density and the critical importance of land use in the province selecting any site for waste disposal would not be advisable for the current or future generations.

Table 2 Quantitative information output of location analysis by weighting method and fuzzy standardization in the area of Mazandaran province (areas covered by conflict with environmental criteria)

Number of environmental criteria	The ratio of the violation area to the total area of Mazandaran province (%)	Area of restricted violation areas (ha)
0	0	0
1	0	0
2	0	0
3	0	0
4	0	0
5	0	0
6	0.0077	1835.4
7	0.0690	16353.3
8	0.2502	59339.6
9	0.8561	203037.1
10	2.6894	637829.5
11	7.7463	1837154.8
12	11.3664	2695736.3
13	15.3405	3638251.7
14	21.7650	5161944.8
15	22.5970	5359265.3
16	13.4853	3198266.5
17	3.7233	883053.0
18	0.1038	24612.6
Sum	100	23716680

Based on Table 2, it is evident that the entire area of Mazandaran Province conflicts with at least six and up to 16 environmental criteria. Therefore, selecting a suitable site for waste disposal in Mazandaran based on national regulations is technically infeasible. As the results show, no location fully meets all the required criteria for waste disposal. Spatial analysis revealed that 22.6% of Mazandaran Province's area conflicts with 15 environmental criteria. For the remaining areas, the conflicts decrease, but no zones with fewer than six conflicting criteria were identified. Thus, from a spatial analysis perspective, considering the technical environmental criteria, no suitable locations can be found. These findings remain consistent when using the Boolean approach. Even with the application of standardized maps and weighted orderings, no suitable site was identified. Similarly, in other weighted scenarios from previous studies, no site satisfying all the technical and legal requirements for special waste disposal based on a scoring scale from 0 to 255 was found. Shayan et al. (2018) similarly concluded that the optimal landfill sites are near transportation routes, while the least suitable are near

human settlements. Of the 4626 km² area of Zarindasht County, only 3.83% was deemed completely suitable for waste disposal.

Switching to weighted methods and standardizing maps cannot replace adherence to national laws and environmental regulations. While following all the guidelines, no suitable site for industrial waste disposal can be proposed in Mazandaran Province. However, with adjustments to management strategies and the elimination of certain criteria, limited areas may emerge that require thorough field evaluation. The topographic conditions, valuable vegetation cover, accessibility, and high population and village density in Mazandaran are of critical importance and must be considered in any decision-making process.

4. Conclusion

Mazandaran Province, due to its unique environmental characteristics and the sensitivity stemming from population density and natural resources, requires thorough examination when selecting suitable sites for industrial waste disposal. The aim of this study was to identify and analyze appropriate locations using technical and environmental criteria approved by the Environmental Protection Organization, and to apply advanced analytical methods to ensure that the selected sites comply with environmental standards.

1. According to the results, the major urban waste disposal sites in Mazandaran Province currently have very low environmental ratings. In other words, they have been established in prohibited or low-suitability areas without proper consideration of environmental principles.

2. The findings of this study, derived from both Boolean and weighted ranking methods, indicate that there are no waste disposal sites in Mazandaran Province that fully adhere to the environmental criteria set by the Environmental Protection Organization and the special and industrial waste disposal guidelines.

3. Moreover, from a locational perspective, the current urban waste storage centers in Mazandaran Province are situated in some of the worst possible locations. There is no site available for the disposal of special and industrial waste that meets all the technical and environmental disposal criteria.

Some limitations of this research include restricted access to more up-to-date data and the complexities associated with multi-criteria analysis. For future studies, it is recommended to update the data and expand field studies to conduct more precise analyses, as well as to examine the long-term environmental impacts of selecting waste disposal sites. Additionally, the development of management systems to improve efficiency and reduce environmental risks in the disposal of special industrial waste is suggested.

Conflicts of interest

The authors of this paper declared no conflict of interest regarding the authorship or publication of this paper.

Author contribution

M. Khoshravesh: Writing-review & editing, Supervision; H. Amirnejad: Research Management; R. Norooz Valashedi: Modeling and Results Analysis and K. Ataie Solout: Data Collection

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