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Site selection for wastewater treatment plant using integrated fuzzy logic and multicriteria decision model: A case study in Kahak, Iran

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Original Article

Abstract

One of the environmental issues in urban planning is finding a suitable site for constructing infrastructures such as water and wastewater treatment plants. There are numerous factors to be considered for this purpose, which make decision-making a complex task. We used an integrated fuzzy logic and multicriteria decision model to select a suitable site for establishing wastewater treatment plant in Kahak, Iran. We used super decision software and a geographic information system (GIS) for scoring the parameters. The western part of Kahak was found to be a suitable place for constructing municipal wastewater treatment plant. Our findings indicated that decision makers and policy makers would be able to achieve better results concerning the most suitable location for wastewater treatment plant easily through combining these two models.

KEYWORDS: Fuzzy Logic, Multicriteria Decision Making, Wastewater Treatment Plant, Site Location

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Introduction

Rapid growth of urban settlements together with a change in their usage pattern during recent half century has led not only to increase in urban systems input rate but also it has had great impact on their output rate. One of the important outputs is municipal wastewater, which severely threats natural ecosystems. Hence, it is necessary to take effective steps toward achievement of environmental goals of sustainability through developing treatment plants in suitable sites, but finding a suitable site for this purpose involves considering wide range of criteria that makes decision making complicated. These complexities justify the necessity of a systematic method for analyzing the decision in a framework that processes spatial data; a method which could justify awareness, expert and judgment.[1] Anagnostopoulos and Vavatsikos[2] extended fuzzy-analytic hierarchy process (FAHP) model for determining wastewater treatment plant site. The factors used in this investigation include slope, topography, geology, land use, distance from road, railroad, river, settlements, faults, coastline, etc. They categorized suitable sites for constructing wastewater treatment plant in Rodopi City and identified fuzzy model and network analysis process as a combined suitable model for decision makers in determining a suitable site for wastewater treatment plant. Anagnostopoulos et al.[3] in another study tried to find the most suitable location for wastewater treatment plant of a region using FAHP method. They found out that the combination of multi-criteria decision making model and geographic information system (GIS) is a valuable tool for determining the treatment

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plant site. In their study, they used 4 indices (12 criteria) to achieve their goal.

Deepa and Krishnaveni[4] using analytic hierarchy process (AHP) method and GIS tried to determine a suitable site for decentralized wastewater treatment plant in Shollinganallur region. In their study, they used 5 criteria: Topography, slope, land use, population, and soil.

In these studies, we can find that multicriteria decision making methods such as AHP and also fuzzy model have been identified as common applied models during recent years. Furthermore, they insisted that GIS is the most suitable spatial analysis tool and a combination of different information layers. The most significant point in these studies is that the role of combined models in determining suitable sites for wastewater treatment plant construction is highly significant. Hence, in present study, we used fuzzy and analytic network process (ANP) combined model which has higher capability compared to other decision making models in order to obtain better results. On the other hand, more criteria were considered in present study than previous ones. Based on the criteria and mentioned model, we tried to determine a suitable place for constructing a wastewater treatment plant in Kahak, Iran.

Materials and Methods

In order to facilitate computations and enhance the accuracy in scoring, in present study we used Super Decision Software. The mentioned software is designed based on network analysis process model and it is able to perform paired comparison among elements and clusters, bounded, harmonic and inharmonious matrices and compute the weight of each criterion with highest accuracy.

Due to its various capabilities in the field of spatial analysis, GIS is the other software which is used in these studies; such that Spatial Analyst Extension provides the opportunity to define fuzzy model and develop related maps. On the other hand, this extension with the ability to superimpose raster layers makes development of final map possible. It must be mentioned that some plans from related organizations were prepared with Shp format; but other maps were adopted from main maps. For example, we can refer to topography layer which was obtained from DEM raster layer.

The present study tries to find the most suitable site for constructing wastewater treatment plant in Kahak city using combined model of network analysis and fuzzy process. Increasing the accuracy in final results, matching two mentioned model with data nature (discrete and continuous) and commonality of combined models are of important reasons for selecting fuzzy-ANP combined model.[5] Hence, firstly we introduced and collected the criteria and then we identified the methods of network analysis process separately. Then, using Super Decision software, we performed related computations for the structure of ANP model. In the next step, we determined the thresholds (minimum and maximum) of optimal site for wastewater treatment plant through reviewing the literatures and then we implemented all final data of network analysis process model in database of basic maps related to discrete data (in GIS environment) and with reliance on fuzzy formula we prepared fuzzy maps. Finally, by superimposing all layers, we determined the final area for constructing the wastewater treatment plant (Figure 1).

By reviewing the literatures, we found that each of researchers has used a certain set of criteria for determining suitable site for wastewater treatment plant referred in introduction of present study. Based on these studies, 12 criteria were categorized in the form of two general groups of discrete and continuous indices, such that discrete indices included 6 criteria (soil, slope, topography, geology, land use, and wind) and continuous indices included 6 criteria (distance from main city, underground water, surface water, roads, and settlements).

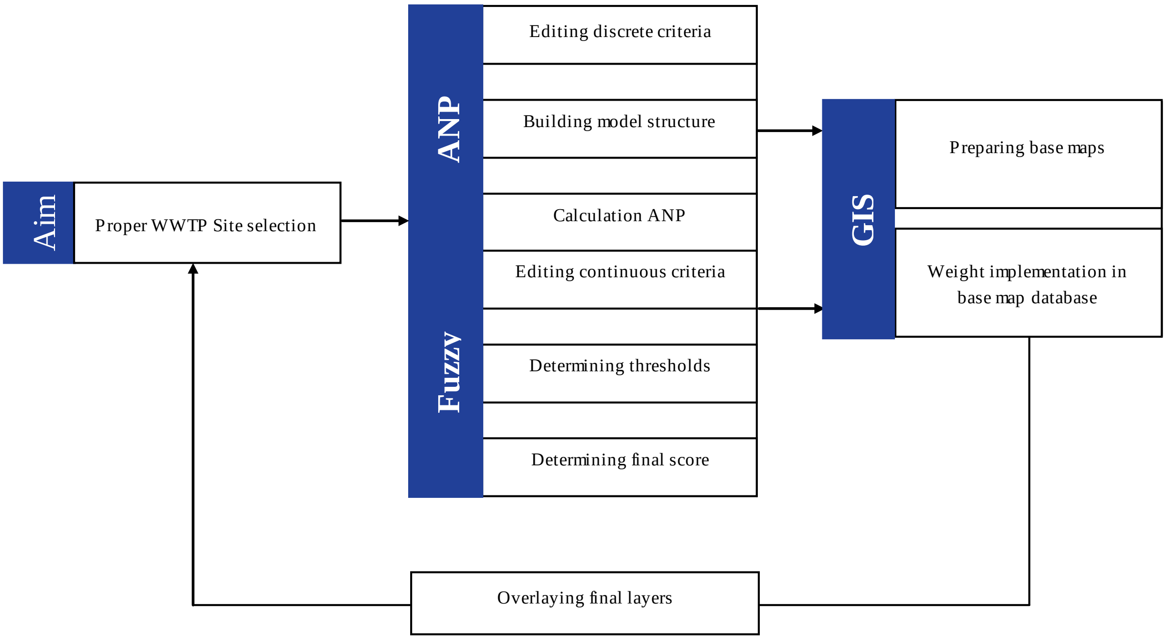


Figure 1. Procedure framework
WWTP: wastewater treatment plant; ANP: Analytic network process; GIS: Geographical Information System

ANP is one of multi-criteria decision making techniques and is a set-up model. This model is designed based on AHP and "Network" to replace "hierarchy".[6]

Some of the fundamental ideas in support of ANP are : (1) ANP is built on the widely used AHP; (2) by allowing for dependence, the ANP goes beyond the AHP by including independence and hence also the AHP as a special case; (3) the ANP deals with dependence within a set of elements (inner dependence), and among different sets of elements (outer dependence); (4) the looser network structure of the ANP makes possible the representation of any decision problem without concern for what comes first and what comes next as in a hierarchy; (5) ANP is a non-linear structure that deals with sources, cycles, and sinks having a hierarchy of linear form with goals in the top level and the alternatives in the bottom level; (6) ANP portrays a real-world representation of the problem under consideration by prioritizing not only just the elements but also groups or clusters of elements as is often necessary; and (7) the ANP utilizes the idea of a control hierarchy or a control network to deal with different criteria, eventually leading to the analysis of benefits, opportunities, costs, and risks. By relying on the control's elements, the ANP parallels what the human brain does in combining different sense data as for example does the thalamus.[7] The main stages of the model can be classified in four categories:

Step I (model construction and problem structuring): The problem should be clearly stated and decomposed into a rational system such as a network. The framework can be determined based on decision-maker opinion via brainstorming or other appropriate methods.[8]

Step II (pairwise comparisons and local priority vectors): The elements are compared pairwisely with respect to their impacts on other elements. The way of conducting pairwise comparisons and obtaining priority vectors is the same as in the AHP. The relative importance values are determined on a scale of 1-9, where a score of 1 indicates equal importance between the two elements and 9 represents the extreme importance of one element compared with the other one. A reciprocal value is assigned to the inverse comparison; that is, $a_{ji}=1/a_{ij}$ where a_{ij}

denotes the importance of the i^{th} element compared with the j^{th} element. Also, a_{ii} =1 is preserved in the pairwise comparison matrix. Then, the eigenvector method is employed to obtain the local priority vectors for each pairwise comparison matrix. To test consistency of a pairwise comparison, a consistency ratio (CR) can be introduced with consistency index (CI) and random index (RI). Table 1 shows the average RI for corresponding matrix size. If the CR is less than 0.1, the pairwise comparison is considered acceptable.[7,9-11] By formulas 1 and 2 it can be calculated from the index weights consistency rate:

(1) $CI=\frac{\lambda_{max}-n}{n-1}$ Eq.

(2) $CR = CI/RI$ Eq.

Step III (supermatrix formation): A supermatrix, known as partition matrix, is formed by setting the local priority vectors on suitable columns. Local priority vectors are classified and occupied in suitable places based on effect flow from one component to another. Supermatrix may consist of zero value. In general, there exists interdependence between clusters, the sum of one column in the supermatrix is mostly bigger than 1. In case the supermatrix is not stochastic, the cluster is weighted and column is normalized to transform into a stochastic matrix where the sum of columns are 1. This matrix can be called as a weighted supermatrix.[12]

Step IV (calculation of global priority vectors and weights): In the final step, the weighted supermatrix is raised to limiting power to get the global priority vectors as in Eq. (3):

(3) $\lim =_{K\to\infty} W^K$ Eq.

If the supermatrix has the effect of cyclicity, there may be two or more N limiting supermatrices. In this case, the Cesaro sum is calculated as in Eq. (4) to get the average priority weights as follows:[13]

(4) $\lim_{K\to\infty}(1/N)\sum W_i^k$ Eq.

Where W is the weighted supermatrix, N indicates the sequence, and k is the exponent determined by iteration.[5]

Zadeh[14] introduced the fuzzy set theory to deal with the uncertainty due to imprecision and vagueness. A major contribution of fuzzy set theory is its capability of representing vague data. The theory also allows mathematical operators and programming apply to the fuzzy domain. A fuzzy set is a class of objects with a continuum of grades of membership.[15]

The fuzzy set theory is a logic that the degree of the membership of each element can be calculated based on it, such that the membership degree of each element in the fuzzy set is defined spectrally among the data between [0,1]. In addition, in this logic in order to make fuzzy data, there are various functions of fuzzy logic.[16]

Among the most important functions, triangular functions, linear function, trapezoidal function, linear function J, etc. could be mentioned. Here, it was tried to determine membership degree of each pixels in the fuzzy logic set by triangular fuzzy logic. This set is defined by three values a ≤ b ≤ c for any number of which a membership function is defined. This membership function has the following formula and diagram (Figure 2).

Kahak is located 30 km from Qom, at longitude of 50° 30°- 51° 00 and latitude of 34°-34° 30° (Figure 3). This town is the center of Kahak district having a population of 2789 based on 2006 census.

In recent decades, rapid growth of the city has caused environmental issues that are increasingly important. Unfortunately, the lack of wastewater treatment is one of the most important environmental problems in the region (Kahak) so that the release of domestic, industrial, commercial, and other types of wastewater in open spaces or disposed of by absorption wells

Table 1. Average ratio of inconsistency for corresponding matrix size10

(n)	1	2	3	4	5	6	7	8	9	10	11	12	13	14	15
Random index (RI)	0	0	0.58	0.90	1.12	1.24	1.32	1.41	1.45	1.49	1.51	1.48	1.56	1.57	1.59

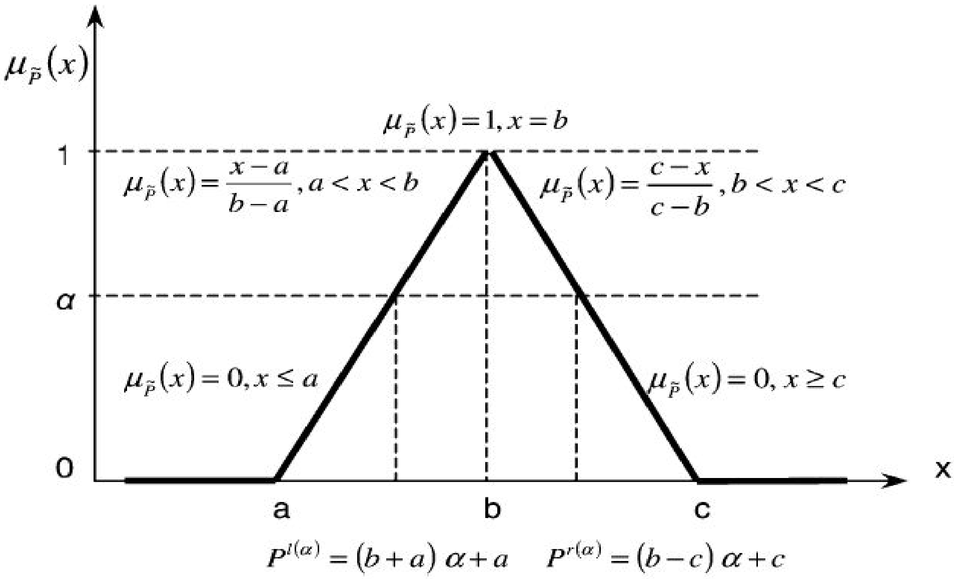


Figure 2. Left and right representation of a TFN, $\tilde{p}'$ adopted from Kahraman et al.[17] In this kind of fuzzy numbers, $\mu_{\tilde{P}}(x)$ is fuzzy function, (b) is the central value with the highest probability, (a) and (c) represent the fuzziness[18]

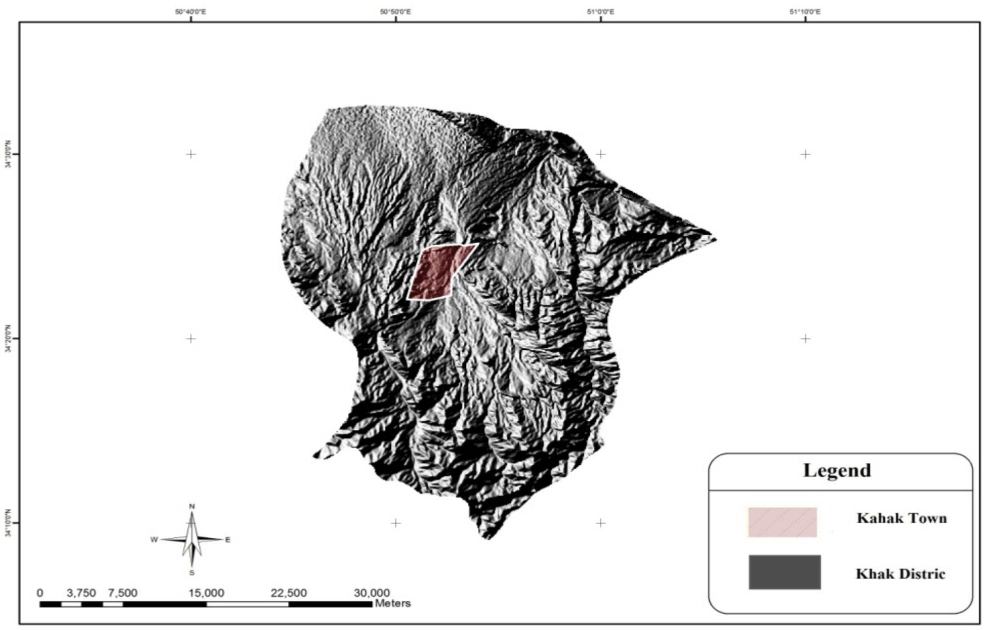


Figure 3. Position of the Kahak Town

has caused both of these methods present a serious threat to ecosystem region. On the other hand, locating infrastructures in the region requires supplying water and construction of municipal wastewater treatment plant that is essential to supply water for irrigation.

Results and Discussion

Making continuous criteria fuzzy

In this part of study, 6 criteria (distance from main city, distance from settlements, distance from faults, distance from roads, distance from main rivers, and penetrating waters) were selected as continuous criteria (Figure 4). The main reason for selecting these criteria and including them in continuous macro-criteria group was that based on long or small distance of wastewater treatment plant site from 6 mentioned criteria, it could have negative or positive consequences from social, economic and environmental aspects for Kahak Town. Hence, the spectral feature of each of these criteria induces the authors to put them in continuous criteria group. But it is necessary to determine maximum and minimum thresholds of each criterion based on performed studies and or available rules in order to achieve better results.

Distance from roads

Anagnostopoulos and Vavatsikos[2] in their study identified 300 meters distance from the main roads for constructing wastewater refinery. We similarly supposed at least 300 meters distance as suitable distance and for which we considered 3000 meters maximum threshold.

Distance from settlements and main city

Meinzinger[19] believes that constructing wastewater treatment plant in 1500 meters distance from main settlements is a suitable distance. In present study, we supposed 550-5000 meters as suitable distance because we believe that small distance of these installations from main settlements would lead to transmission of odor and pollution to city. On the other hand, long distance involves huge costs for constructing infrastructures. For other mall settlements which have more density around the cities, 150-1500 meters seems suitable.

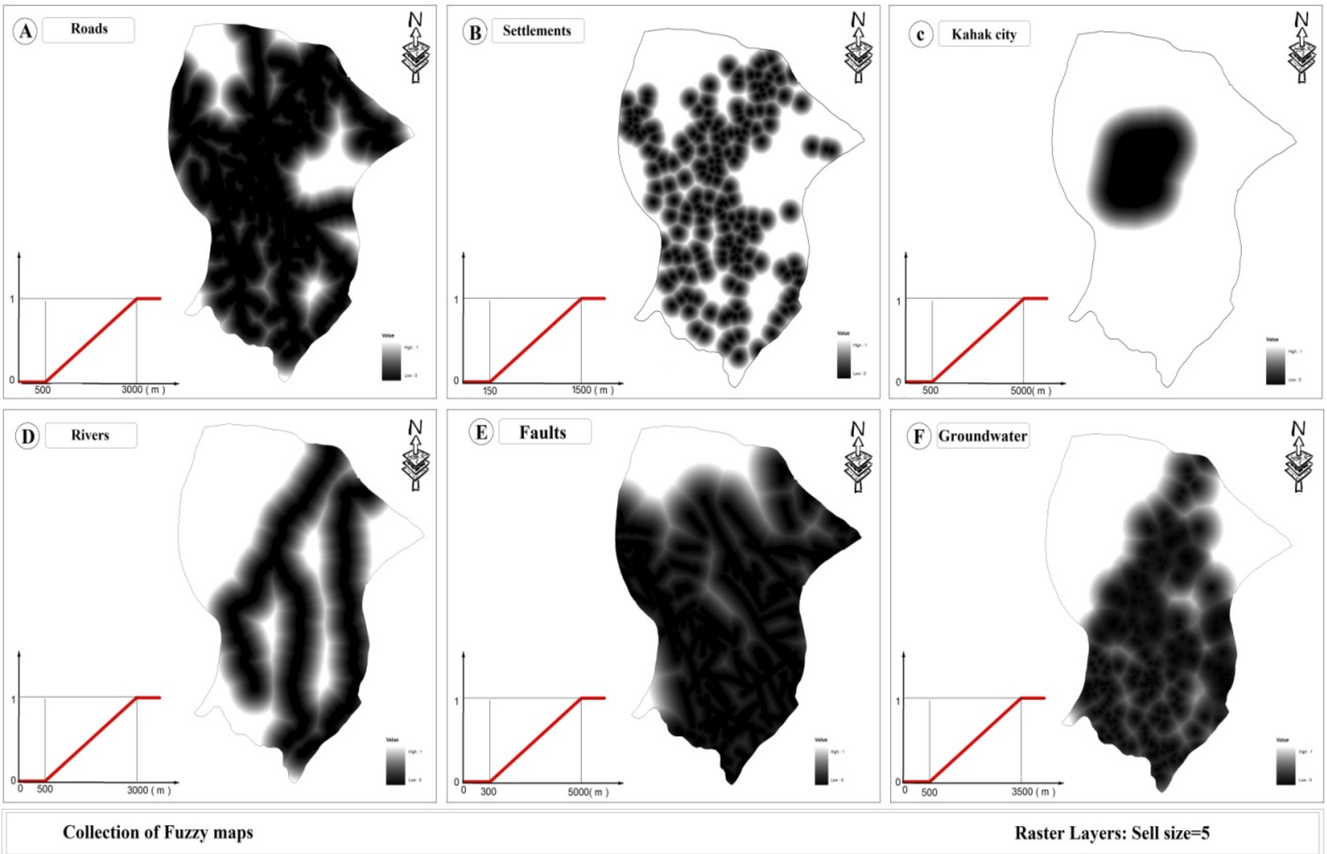


Figure 4. Collection of fuzzy maps

Distance from rivers and faults

In order to protect natural resources, Anagnostopoulos and Vavatsikos[2] identified minimum 500 meters and maximum 3 kilometers from main rivers as a suitable area for constructing wastewater refinery. They also considered minimum 300 meters and maximum 5 kilometers distance from faults for the purpose of their study.

Distance from penetrating waters (well and spring)

Protecting the resources and preventing them from being polluted are of important points emphasized in many studies in terms of finding a suitable site for refinery. Therefore, we considered minimum 500 meters and maximum 3500 meters distance from wells and springs as a suitable area for preventing them from being polluted (Table 2).

Table 2. Minimum and maximum distance for wastewater treatment plant site for defining fuzzy membership functions

	Index	Minimum Distance	Maximum Distance
A	Roads	500	3000
B	Settlements	150	1500
C	Kahak	500	5000
D	Main rivers	500	3000
E	Faults	300	5000
F	Groundwater	500	3500

When all minimum and maximum values for each criterion is determined, we can make all data layers relating to continuous data fuzzy through following steps in GIS environment:

In first step, we computed and determined direct distances from regarded terrains through Spatial Analyst-Distance instruction (ΔX).

In the second step, we used Spatial Analyst-Raster calculation instruction:

$\Delta X/_{X_{MAX}}$B) $\Delta X/_{X_{MAX}}$ A)

ANP calculations for discrete criteria

According to conducted studies concerning locating urban wastewater refinery, the authors selected 6 criteria for this part of research and then based on their similarities they grouped them into two clusters: Physical and ground conditions. Each of these clusters is consisted of 3 criteria: For physical cluster, topography, slope and wind direction' for ground condition cluster, geology, soil and land use were considered. Then, using Super Decision software, we designed and developed ANP model. In this model, each arrow represents the influence of a cluster on other clusters. For example, physical cluster impacts natural cluster and it mutually takes effect. Of course, there is interdependence among internal elements of each cluster that is indicated by an arrow on top of them (in the form of a returning ring to the cluster itself) (Figure 5). From the arrows we can find that 4 main matrices should be formed for ANP calculations because in network analysis process each arrow represents a matrix.

After developing the matrices, paired comparisons among clusters and each element (criteria) must be conducted. In this regard, we asked 5 experts to present their ideas concerning the relative importance of each element relating the location of municipal wastewater refinery. After integrating the ideas of professionals, the related data were entered in Super Decision software through which paired comparisons were conducted. After completing the paired comparisons among the clusters and their elements, we obtained compatibility rate equal to zero and this rate was accepted. By incorporating the results of each matrix into one matrix, we obtained primary super-matrix in which the sum of each line is more than one. Therefore, Super Decision software forms harmonious super-matrix in line with normalizing the primary super-matrix (Figure 6). The final results of superiority of priorities are indicated in 6 subgroups in numerical and graphical forms in figure 7. As one can see, the criterion of region's slope with normalized score of 0.76 is more important than others and then we have land use of region with 0.68 score in determining the place of municipal wastewater treatment plant of Kahak city compared to other parameters.

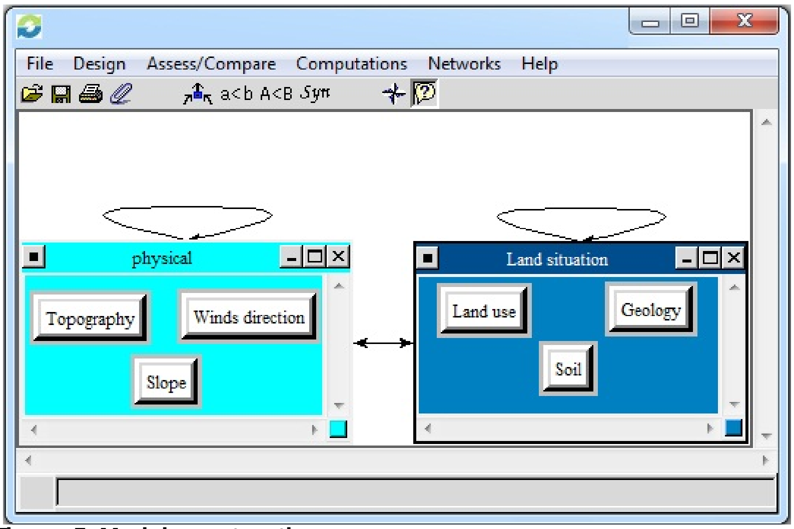
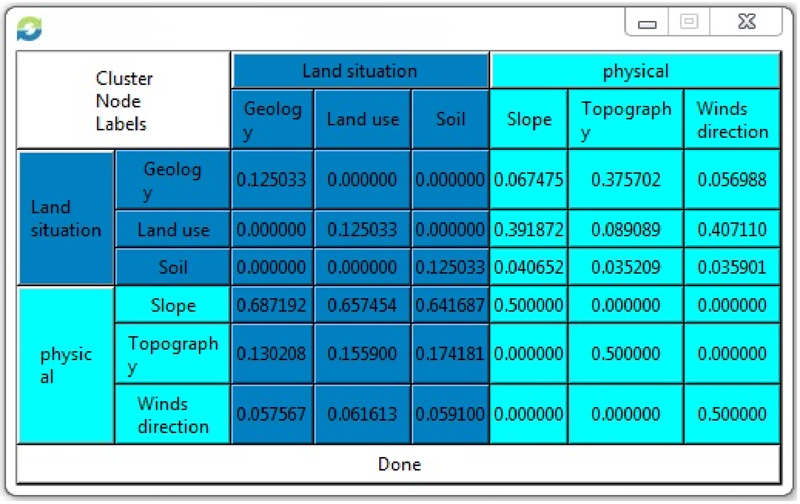


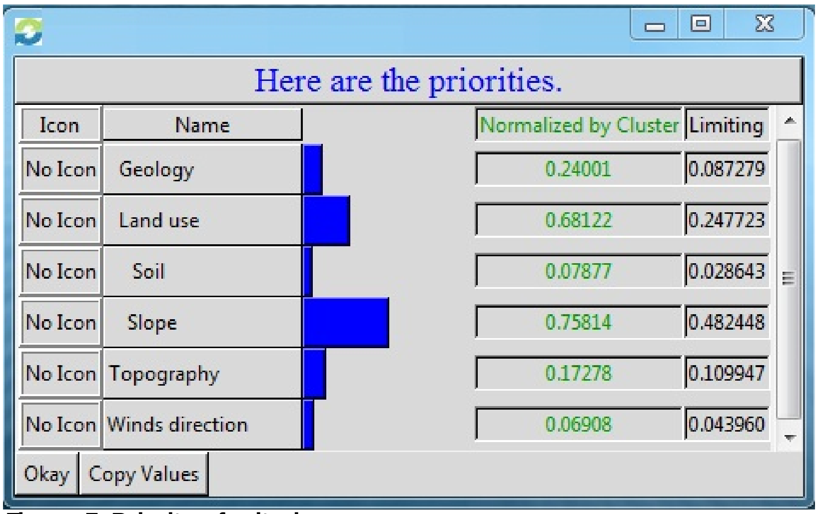
Figure 5. Model construction



Cluster Node Labels		Land situation			physical		
		Geology	Land use	Soil	Slope	Topography	Winds direction
Land situation	Geology	0.125033	0.000000	0.000000	0.067475	0.375702	0.056988
	Land use	0.000000	0.125033	0.000000	0.391872	0.089089	0.407110
	Soil	0.000000	0.000000	0.125033	0.040652	0.035209	0.035901
physical	Slope	0.687192	0.657454	0.641687	0.500000	0.000000	0.000000
	Topography	0.130208	0.155900	0.174181	0.000000	0.500000	0.000000
	Winds direction	0.057567	0.061613	0.059100	0.000000	0.000000	0.500000

Done

Figure 6. Weighted supermatrix



Here are the priorities.

Icon	Name	Normalized by Cluster	Limiting
No Icon	Geology	0.24001	0.087279
No Icon	Land use	0.68122	0.247723
No Icon	Soil	0.07877	0.028643
No Icon	Slope	0.75814	0.482448
No Icon	Topography	0.17278	0.109947
No Icon	Winds direction	0.06908	0.043960

Okay Copy Values

Figure 7. Priority of criteria

All normalized scores were reevaluated by 1-9 time scale in order to determine the relative importance of each sub-criterion (variables). Using GIS, all scores of each of sub-criteria were incorporated in related 6 layers. In last step, using Spatial Analyst Extension, all 6 layers were converted to raster format with Sell Size 5 to be prepared for final computations (Figure 8).

Combination of Fuzzy-ANP models

In order to implement the model through Kahak region, all layers were prepared in Shp format. Based on triangular fuzzy function, data layers of continuous criteria were converted to fuzzy form. All layers were fuzzified in GIS environment through Spatial Analyst extension. On the other hand, for weighting the discrete layers, a new column was developed in database of basic maps and obtained final scores were assigned to corresponding layers using Super Decision software. Then, all discrete layers which were in vector form were converted to raster layers with Sell Size 5 using Extension (Spatial Analyst).

In the final step, it was required to combine data layers. There are different methods for combining data layers but in present study we used Raster layers superimposition with sell size 5 using Extension (Spatial Analyst- Raster Calculator). After integrating the layers, the value of each pixel was determined and it was found that based on figure 9, western part of Kahak city is the most suitable location for constructing wastewater treatment plant.

Conclusion

In present study, application of two decision making tools, i.e. fuzzy multi criteria and ANP models in combined manner for determination of a suitable location for constructing wastewater treatment plant was identified. Precisely, by the help of studies performed up to now concerning determination of a suitable location for constructing wastewater treatment plant, we could determine main indices and criteria and moreover we divided the criteria to two groups called discrete and continuous ones so that they

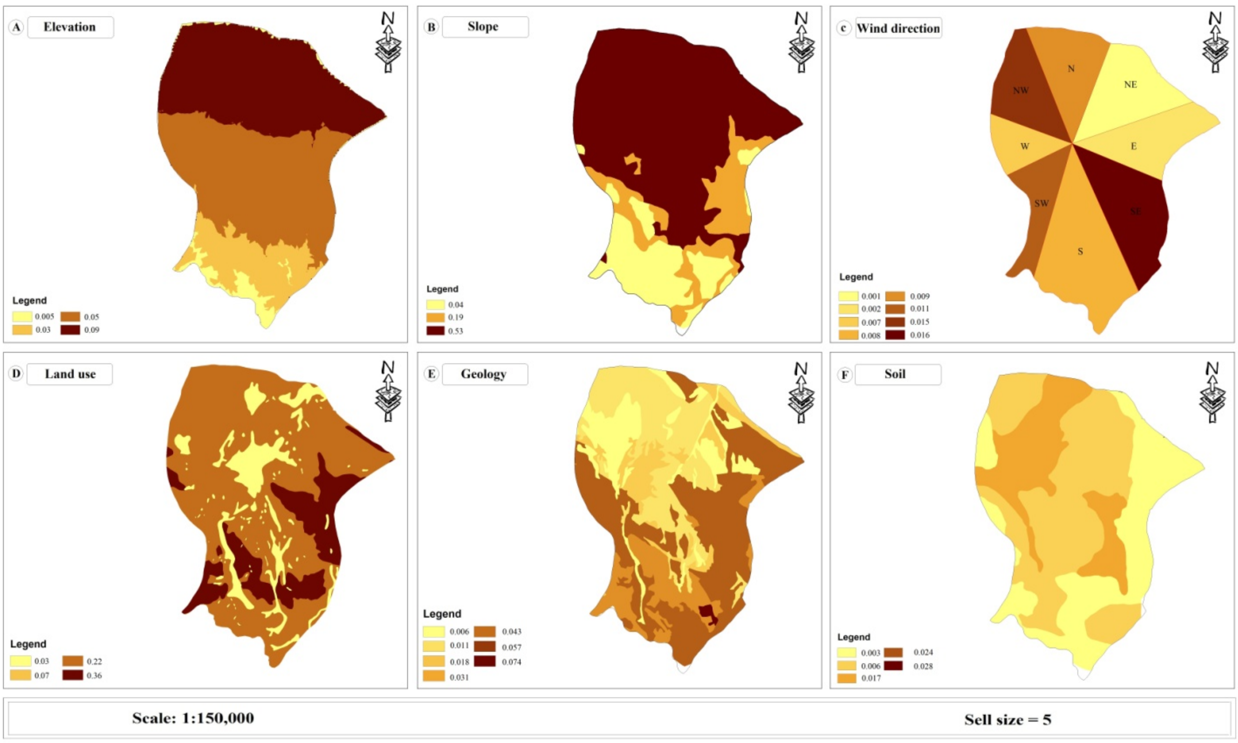


Figure 8. The raster maps calculated by ANP model

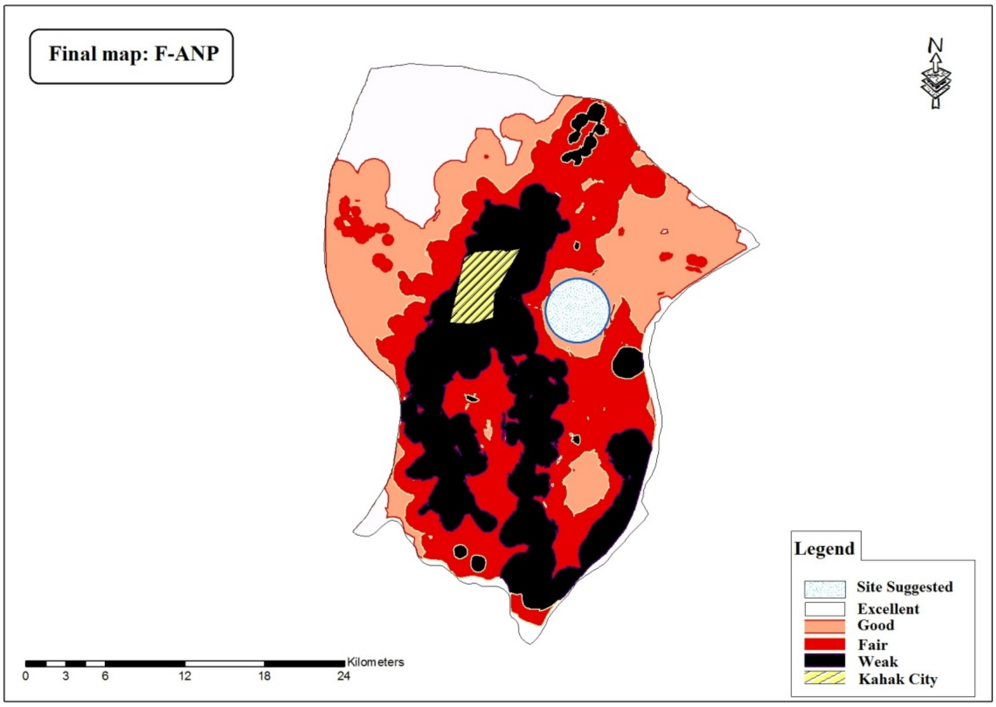


Figure 9. Final fuzzy logic and analytic network process map indicating the most suitable site for wastewater treatment plant

matched the combined model. After conducting the computations, incorporating and combining the data in GIS software environment, the western part of Kahak was found to be a suitable place for constructing municipal wastewater refinery. These findings indicated that through combining these two models, decision makers and policy makers would be able to achieve better results concerning the most suitable location for wastewater treatment plant easily. In previous studies, the authors had used this model for finding a suitable location for landfill, but the difference is that in the present study, computational software such as Super Decision for decision making was used and the results indicated that this software makes the computations easier and it reduces the possibility of error. Application of newer models and more criteria is another difference in this study compared to previous studies.

Conflict of Interests

Authors have no conflict of interests.

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