Combining Fuzzy Analytic Hierarchy Process and GIS to Select the Best Location for a Wastewater Lift Station in El-Mahalla El-Kubra, North Egypt

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***Abstract*-- Determining the best location is a complex process that faces the Decision makers. In El-Mahalla El-Kubra, Egypt this problem exists in selecting the best location for wastewater lift station of an under-construction industrial sewage system. The site selection problem comes with criteria that determine the best location. Dealing with real life situation and experts' judgments involves uncertainty. To solve this problem, we designed a model containing Multi-Criteria Decision Making (MCDM) technique that is Analytical Hierarchy Process (AHP) with fuzzy theory to handle the uncertainty situations and Geographical Information System (GIS) to determine the best location. An application adopting the FAHP idea was developed to calculate weights of the criteria of the site. The GIS was used to overlay and generate criteria maps and suitability map. The study ends with an assessment of proposed sites to the generated suitability map.**

***Index Term*— Geographical information system (GIS), multi-criteria decision making (MCDM), and fuzzy analytical hierarchy process (FAHP).**

I. Introduction

E1-Mahalla El-Kubra is a large industrial and agricultural city in northern Egypt, located in the middle of the Nile Delta on the western bank of the Damietta branch. It has an international and national sound with its textile spinning and weaving industries.

For many years, the sewage network of the city was used for both human wastes and industrial wastes. But recently there was a big increase in the field of spinning and weaving which created the necessity of establishing a stand-alone industrial sewage network. The government decided to build an independent industrial sewage network in El-Mahalla. This new sewage network needs a lift station to leverage the wastes to the treatment station. This lift station should be located nearby its sewage network. But there was a problem facing the planners that is determining the best location of this lift station. Determining the best site from a number of alternative sites is a difficult and complex process. Site selection is a kind of decision making process that requires criteria to be weighted and alternatives to be evaluated and ranked. Integration between Multi criteria Decision Making (MCDM) and GIS is needed to solve the site selection problem as GIS is used to handle the spatial aspect of the problem and MCDM is used to calculate weights of the criteria and ranking of alternatives.

Selecting a site for a wastewater lift station is a complex decision making process. Lift station site selection is dependent on a number of factors and constraints including: topography, access, availability of power supply, floodplain, site drainage, land use, aesthetic and odor concerns, overflow potential and impact to the environment. These factors shall be considered when selecting the lift station site. Identifying these evaluation criteria, defining the effects of them on each other, assessing their importance, and choosing a particular location necessitate a well-designed multiple criteria decision making (MCDM) based evaluation [1].

One of the useful methods of MCDM is Analytical Hierarchy Process (AHP) introduced by Saaty (1980) [2], it plays an important role in selecting alternatives [3], [4]. AHP has become one of the most widely used methods for the practical solution of MCDM problems [5], [6]. AHP uses understanding and informed knowledge without the need of specific data [7]. But the main shortage of AHP is that it deals with people's expert judgment as a crisp number between 1 and 9 and their Eigen values, this doesn't handle the uncertainty associating to these judgments. In order to overcome that incompetence, Fuzzy set is used within AHP calculations to determine the best alternative [8], [6]. The combination between AHP and fuzzy set leads to more flexibility in judgment and decision making. Fuzzy AHP (FAHP) reflects human thinking as it uses approximate information and uncertainty to generate decision in addition to inheritance of the advantages of AHP, ease of handling qualitative and quantitative data, use of hierarchical structure, pairwise comparison, reduce inconsistency, and generates priority vectors [4].

There is no evidence in the literature that any of these publications were applied to a wastewater lift station problem or applied in Egypt or a region within, using FAHP and GIS. This is the most powerful motivation to conduct this study. In this study, GIS is used to analyze and classify maps according to the determined criteria into predefined classes or buffer zones. An application is developed using visualbasic.net adopting FAHP to calculate weights of the criteria using triangular fuzzy numbers (TFNS). Integration between GIS and FAHP is performed to obtain the suitability map. Then, the proposed sites were assessed regarding the generated suitability map. The rest of this paper is organized as follow: a brief exploration of the history about the theory used in this study and an explanation of the theory of using of FAHP in section 2; in section 3, the integration between FAHP and GIS containing the study area, data collection, methodology and analysis; in section 4, results and discussion, and finally section 5 the conclusion.

II. Background

A. Literature Review

Vivien Y.C. Chen et al., (2011) designed a fuzzy decision support system in multi-criteria analysis approach for selecting the best plan strategies in environment watershed. A questionnaire was used to find out from three related groups comprising 15 experts. The fuzzy theory was used to deal with subjectivity and vagueness in the criteria and alternatives of the selection process. This research was applied to an example of an environment-watershed plan work in Taiwan, to illustrate the effectiveness and usefulness of the proposed approach. The result was useful for destination planning and the sustainability of watershed tourism resources as well [9].

Onut S. Et al., (2010) proposed a combined fuzzy MCDM with GIS for selecting a shopping center site in Istanbul, Turkey. FAHP was used for assigning weights of the criteria of the site selection and fuzzy Technique for Order Preference by Similarity to Ideal Solution (TOPSIS) to rank the alternative sites. Then, a sensitivity analysis is performed for getting accurate results. Eight criteria were determined and six alternative sites were proposed for the shopping center location. This study results in that the proposed method is practical for ranking alternatives with respect to multiple conflicting criteria for the large scale problems [10].

Vahidnia M.H. et al., (2009) used GIS with FAHP to determine the optimum site for a new hospital in Tehran urban area, Iran. A well distributed network of hospitals considering minimal time, pollution, and cost was created. Three methods were used to estimate the total weights and priorities of the alternative sites, which are fuzzy extent analysis, center of area defuzzification, and α-cut method. Five criteria were determined and five sites were proposed for the new hospital site. This study results in nearly identical priorities of the five alternative sites with the three methods [4].

B. Fuzzy Analytical Hierarchy Process (FAHP)

FAHP is an extension of AHP. The assessment of different criteria requires using of fuzzy number. While, AHP based on the use of crisp numbers. FAHP overcomes that defect in AHP. Since fuzziness is a common characteristic of decision making problems, the FAHP method was developed to address this problem [11].

Fuzzy set theory [12] is a mathematical theory designed to model the fuzziness of real world situations.

A fuzzy number is a special fuzzy set $F = \{(x, \mu f(x), x \in R\}$, where x takes its values on the real line, R: $-\infty \leq x \leq 1$ and $\mu f(x)$ is a continuous mapping from R to the closed interval [0, 1]. A triangular fuzzy number (TFN) expresses the relative strength of each pair of elements in the same hierarchy and can be denoted as M = (l, m, u), where $l \leq m \leq u$. The parameters l; m; u; indicate the smallest possible value, the most promising value, and the largest possible value respectively in a fuzzy event. Triangular type membership function of M fuzzy number can be described as in Eq. (1), Fig. (1) [13]. When l = m = u, it is a nonfuzzy number by convention.

$$\mu_f = \begin{cases} \frac{x-1}{m-1}, & l \leq x \leq m \\ \frac{u-x}{u-m}, & m \leq x \leq u \\ 0, & otherwise \end{cases} \quad (1)$$

Many FAHP methods based on triangular fuzzy numbers have been proposed [13]. This study employs fuzzy extent analysis [13], which is easier to compute than other FAHP approaches.

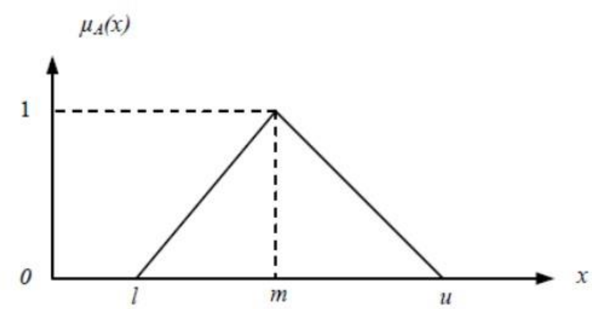

Fig. 1. Fuzzy triangular number.

By using TFNs via pairwise comparison, the fuzzy judgment matrix Ã (aij) can be expressed mathematically as:

$$\tilde{A} = (\tilde{a}_{ij})_{n \times n} = \begin{bmatrix} (1,1,1) & (l_{12}, m_{12}, u_{12}) & \dots & (l_{1n}, m_{1n}, u_{1n}) \\ (l_{21}, m_{21}, u_{21}) & (1,1,1) & \dots & (l_{2n}, m_{2n}, u_{2n}) \\ . & . & .. \\ . & . & .. \\ (l_{n1}, m_{n1}, u_{n1}) & (l_{n2}, m_{n2}, u_{n2}) & \dots & (1,1,1) \end{bmatrix} \quad (2)$$

Where $\tilde{a}_{ij}=(l_{ij}, m_{ij}, u_{ij})$ and $\tilde{a}_{ij}^{-1}=(1/u_{ij}, 1/m_{ij}, 1/l_{ij})$ for i,j=1,.....,n and i ≠ j.

The steps of Chang's fuzzy extent analysis can be summarized as follows:

1. Sum each row of the fuzzy comparison matrix Ã. Then normalize the row sums (obtaining their fuzzy synthetic extent) by the fuzzy arithmetic operation

$$\acute{S}_i = \sum_{j=1}^{n} \tilde{a}_{ij} \otimes \left[\sum_{k=1}^{n}\sum_{j=1}^{n} \tilde{a}_{jk}\right]^{-1} \quad (3)$$

$$= \left(\frac{\sum_{j=1}^{n} l_{ij}}{\sum_{k=1}^{n}\sum_{j=1}^{n} u_{jk}}, \frac{\sum_{j=1}^{n} m_{ij}}{\sum_{k=1}^{n}\sum_{j=1}^{n} m_{jk}}, \frac{\sum_{j=1}^{n} u_{ij}}{\sum_{k=1}^{n}\sum_{j=1}^{n} l_{jk}}\right) \quad (4)$$

where ⊗ denotes the extended multiplication of two fuzzy numbers. These fuzzy triangular numbers are known as the relative weights for each alternative under a given criterion, and are also used to represent the weight of each criterion with respect to the total objective. A weighted summation is then used to obtain the overall performance of each alternative.

2. Compute the degree of possibility for $\acute{S}_i \geq \acute{S}_j$ by the following equation:

$$V(\acute{S}_i \geq \acute{S}_j) = \sup_{y \geq x} [\min(\acute{S}_j(x), \acute{S}_i(y))] \quad (5)$$

This formula can be equivalently expressed as:

$$V(\acute{S}_i \geq \acute{S}_j) = \begin{cases} 1 & m_i \geq m_j \\ \dfrac{u_i - l_j}{(u_i - m_i) + (m_j - l_j)} & l_j \leq u_i \; i,j=1,....,n; j \neq i \\ 0 & otherwise \end{cases} \quad (6)$$

Where $\acute{S}_i = (l_i, m_i, u_i)$ and $\acute{S}_j = (l_j, m_j, u_j)$ (7)

Fig. (2) illustrates this degree of possibility for two fuzzy numbers.

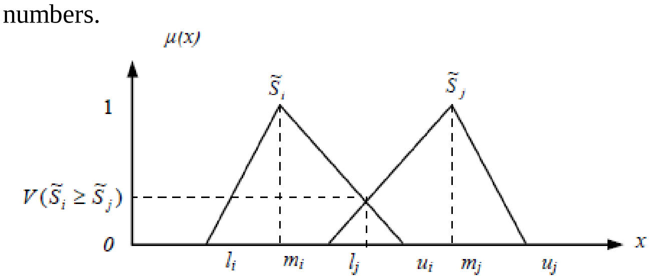

Fig. 2. The degree of possibility V (Śi ≥ Śj).

3. Estimate the priority vector $W = (w_1,.....,w_n)^T$ of the fuzzy comparison matrix Ã as follows:

$$W_i = \frac{l_i + u_i + m_i}{3}, i = 1,....,n \quad (8)$$

In order to rank the criteria the TFN should be defuzzified, so we used a simple centroid method.

4. Finally, the calculated weights of each criterion were normalized as follows:

$$NW_i = \frac{w_i}{\sum_{j=1}^{n} w_j}, j = 1,....,n \quad (9)$$

Where

$$\sum_{i=1}^{n} NW_i = 1, i = 1,....,n$$

In order to perform a pairwise comparison among fuzzy parameters, linguistic variables have been defined for several levels of preference (Table I). The fuzzy triangular numbers used to represent these preferences are depicted in Fig. (3).

To determine if the comparisons are consistent or not a Consistency Ratio (CR) is calculated by the formula [10]:

$$CR = \frac{CI}{RI} \quad (9)$$

Where CI= Consistency Index.

$$CI = \frac{\lambda_{max} - n}{n-1} \quad (10)$$

TABLE I
TRIANGULAR FUZZY NUMBER OF LINGUISTIC VARIABLES USED IN THIS STUDY.

Linguistic variables	Triangular fuzzy numbers	Reciprocal triangular fuzzy numbers
Extremely strong	(9,9,9)	(1/9,1/9,1/9)
Very strong	(6,7,8)	(1/8,1/7,1/6)
Strong	(4,5,6)	(1/6,1/5,1/4)
Moderately strong	(2,3,4)	(1/4,1/3,1/2)
Equally strong	(1,1,1)	(1,1,1)
Intermediate	(7,8,9), (5,6,7), (3,4,5), (1,2,3)	(1/9,1/8,1/7), (1/7,1/6,1/5), (1/5,1/4,1/3), (1/3,1/2,1)

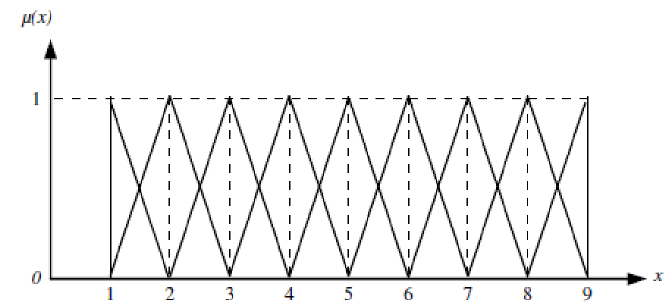

Fig. 3. Triangular fuzzy numbers corresponding to linguistic variables representing levels of preference.

Where λ = average value of consistency vector and n= number of criteria.

RI= random index, the consistency index of a randomly generated pairwise comparison matrix, simply obtained from the table of Random Inconsistency Indices table (II).

The CR is designed in such a way that if CR < 0.10, the ratio indicates a reasonable level of consistency. However, if CR > 0.10 the value of the ratio is indicate inconsistent judgments [15].

TABLE II
RANDOM CONSISTENCY INDEX (RI)

N	1	2	3	4	5	6	7	8	9	10
RI	0	0	.58	.9	1.12	1.24	1.32	1.41	1.45	1.49

III. INTEGRATING AHP WITH GIS

Fig. (4) shows the methodology used in this study. The initial stage is data collection stage, in which spatial data about the problem is collected and experts' measurements of the criteria as well. There are three phase determined in our methodology. Phase I related to GIS analysis, covering converting collected vector maps to raster and spatial analysis functions (distance analysis and reclassify).while calculating criteria weights is in phase II using a developed tool adopting FAHP principal and also calculate the Consistency Ratio for the verification of the consistency of the input data. Finally, phase III in which the integration between criteria weights and Maps is accomplished producing the suitability map which has the best locations for the lift station and with little visualization effort the best location is determined.

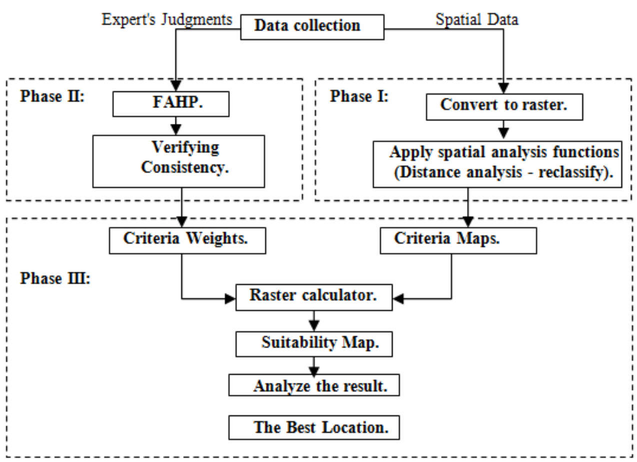

Fig. 4. The methodology.

A. Study Area

The study is conducted in El-Mahalla El-Kubra, Gharbia, Egypt. The area extends from 31°10'12" east to 30°58'12" north as shown in Fig. (5). El-Mahalla El-Kubra is a large industrial and agricultural city in Egypt, located in the middle of the Nile Delta on the western bank of the Damietta branch. It is known for its dominant textile industry. It is famous in the Middle East for the industry of spinning and weaving.

For many years the sewage network of the city was used for both human wastes and industrial wastes. But recently there was a big increase in the field of spinning and weaving which created the necessity of establishing a stand-alone industrial sewage network. In 2000, the government decided to build an independent industrial sewage network in El-Mahalla. This new sewage network normally needs a lift station to leverage the wastes to the treatment station. This lift station should be located nearby its sewage network. But there was a problem facing the planners that is determining the best location of this lift station.

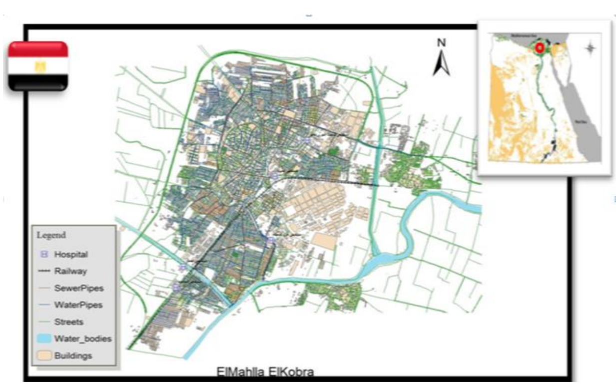

Fig. 5. Location of the study area.

B. Data Collection

Spatial data were obtained from the company of drinking water and sanitation in Gharbia governorate, Egypt. Then, layers of the selected area were generated and new layers were created using ARC/GIS operations. Criteria importance to each other was obtained from experts using 1-9 scale to generated pairwise comparison.

C. Methodology

Three steps were followed; to determine the best location; which are: determining the criteria, calculating criteria weighting, and manipulation and analysis.

Determining the Criteria

The criteria related to this study in Fig. (6) are described below [16], [17], [18]:

1. Distance from residential areas: The lift station should be located at least 500 feet from any buildings or houses to avoid environmental pollution.
2. Access Road: Wastewater lift stations shall be constructed with adequate access for maintenance vehicles including vactor trucks with low-hanging hose reels. All weather vehicular access shall be provided at all sites. All sites shall have a minimum 16 foot wide paved access road/drive having a maximum slope of 12 percent.
3. Topography: soil capability with respect to land grading and land use.
4. Area: Adequate room and turning radius shall be provided so that the boom truck with a wheel base of 14 feet and a turning radius of 44 feet may turn into the site and park inside the site without encroaching on the street or sidewalk.
5. Existing Utilities: avoid intersecting with utilities lines (Communications, Power, sewer and Water Connections).

Slope criterion is ignored as the study area has no slope. The proposed sites with area smaller than required are eliminated. Existing utilities were erased from Land use layer to avoid sites intersected with existing utilities.

Calculating Criteria weighting

All the criteria above are obtained after consulting the relevant experts. Criteria scores were determined according to the scale introduced by Saaty [2] to represent score value of 9 to 1. The bigger score value the more importance rank of criteria. The importance of each criterion relative to other criteria is shown by criteria weighting.

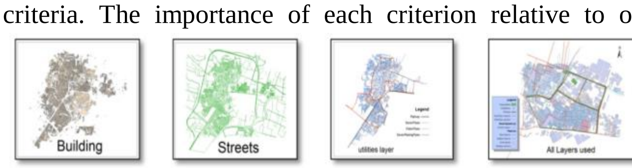

Fig. 6. Location of the study area.

The results of the criteria scoring to assess the relative importance between two criteria are used in a visualbasic.Net application that applies a pairwise comparison technique and FAHP to calculate the weights and consistency ratio as shown in Fig. (7) and table (III -V).

TABLE III
PAIRWISE COMPARISON OF THE STUDY.

Criteria	1	2	3	4
1. Distance from residents	1	5	1/5	1/3
2. Access Road	1/5	1	1/9	1/5
3. Land Use	5	9	1	3
4. End of Sewer	3	5	1/3	1

TABLE IV
THE FUZZY JUDGMENT MATRIX OF THE STUDY

Criteria	1	2	3	4
1. Distance from residents	(1,1,1)	(4,5,6)	(1/6, 1/5, 1/4)	(1/4,1/3,1/2)
2. Access Road	(1/5, 1/5, 1/4)	(1,1,1)	(1/9,1/9,1/9)	(1/4, 1/5, 1/6)
3. Land Use	(4,5,6)	(9,9,9)	(1,1,1)	(2,3,4)
4. End of Sewer	(2,3,4)	(4,5,6)	(1/4,1/3,1/2)	(1,1,1)

TABLE V
THE FUZZY EVALUATION OF THE STUDY

Criteria	Fuzzy number	Normalized weights
1. Distance from residents	(0.132563, 0.184673, 0.257380)	0.185724
2. Access Road	(0.035350, 0.042714, 0.053506)	0.042525
3. Land Use	(0.358208, 0.508794, 0.664207)	0.505691
4. End of Sewer	(0.177430, 0.263819, 0.381919)	0.266060
λ_{max} = 4.254086	CI= 0.084695	CR = 0.094106 ($\leq$ 0.1).

Manipulation and Analysis

In this study, layers overlay, to raster conversion, clipping processes using GIS function and calculating criteria weight using an application based on FAHP technique makes out the manipulation of this study as shown in Fig. (7, 8, 9, and 10).

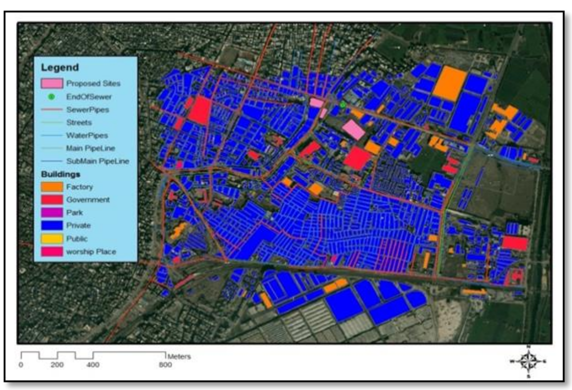

Fig. 7. The layers created in Arc/GIS.

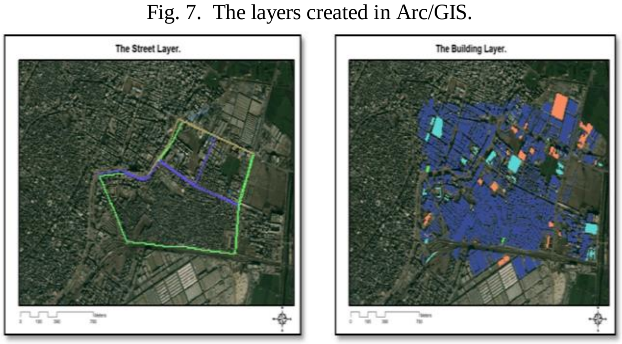

Fig. 8. The layers after applying to raster operations.

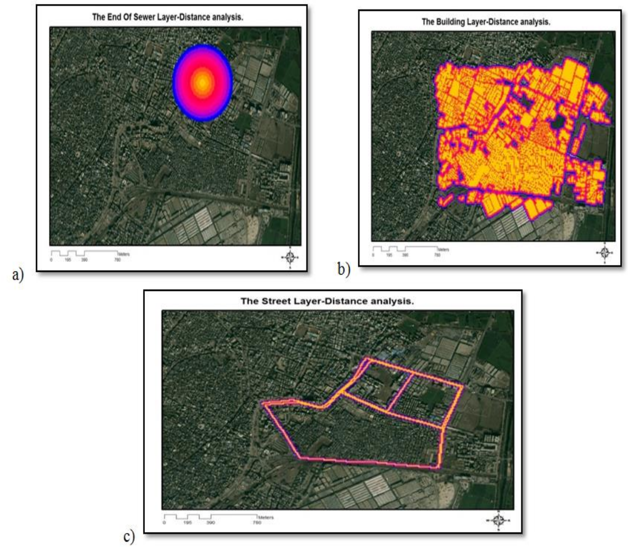

Fig. 9. The layers after applying distance operations. (a) The distance analysis for End Of Sewer Layer; (b) The distance analysis for Building Layer; (c) The distance analysis for Street Layer.

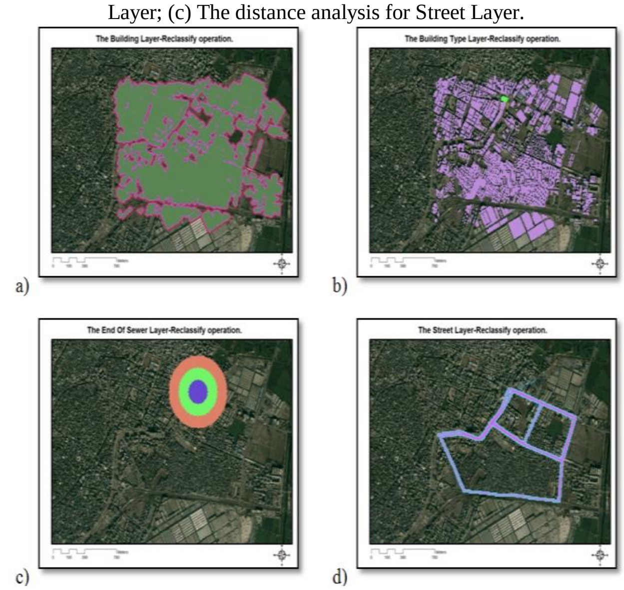

Fig. 10. The layers after applying spatial analysis- reclassify operations. (a) The Reclassify operation for Building Layer; (b) The Reclassify operation for Building Type Layer; (c) The Reclassify operation for End Of Sewer Layer; (d) The Reclassify operation for Street Layer.

Finally, suitability map for the lift station will be generated. Suitability map resulted by integrating criteria weights from FAHP with the criteria maps into raster calculator function in ARG/GIS software.

This result will present a rank of highest and lowest suitability areas. Then suitability classification is divided into three classes: high suitability, medium suitability and low suitability Fig. (11).

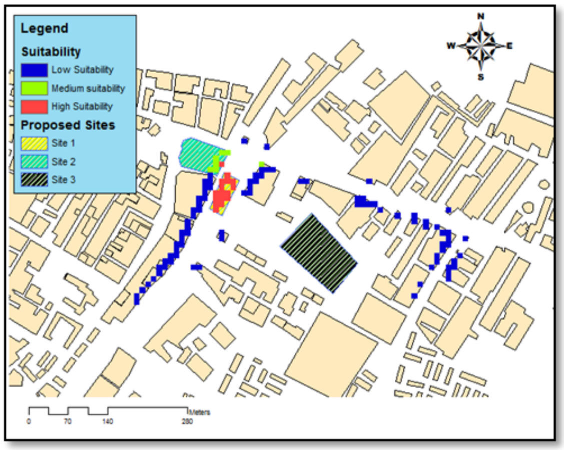

Fig. 11. suitability Map for a wastewater lift station.

Fig. 12. The Proposed Sites map.

IV. Result and Discussion

The criteria considered when determining the suitable location: distance from residents, access Road, existing utilities, land use, end of sewer and area. Existing utilities criterion is a constraints which means the suggested sites cannot intersect with existing utilities. An area criterion is also a constraint as sites with area smaller than the required are ignored. Using GIS capabilities: Criteria Maps were converted to raster then they were classified into three classes: high suitability, medium suitability and low suitability. The results are shown in Fig. (10).

Using a developed application using VisualBasic.Net adopting MCDM –FAHP, the expert's judgments were fed into the application designed and the result shown in Fig. (13).

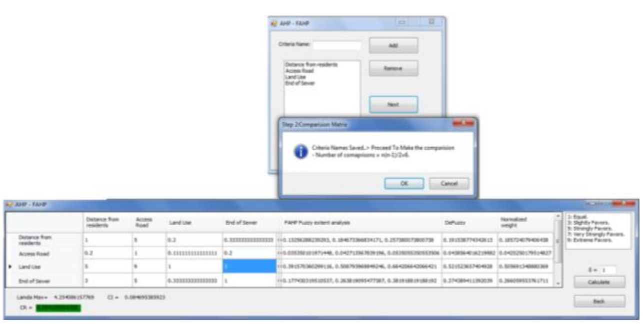

Fig. 13. The calculated weights in the application.

The calculated CR was 0.094106 from Eq. (9) indicates a reasonable level of consistency in the pairwise comparisons and the weights are accepted. Then, the integration between GIS and FAHP weights is done using Spatial Analyst extension of Arc/GIS (Raster Calculator) to multiply weights obtained with the Criteria Maps. The result is the suitability map shown in Fig. (11). Then the map was classified into high suitability, medium suitability and low suitability.

By overlaying the proposed sites map - Fig. (12) - with the generated suitability map - Fig. (11) - , we concluded that site1 is the most suitable site, site 2 has medium suitability and site 3 is unsuitable as shown in Fig. (12) and (Table VI). By comparing the results with the criteria determined for the study and the vector weights which based on the experts opinion we found that site 1 which is the most suitable site had a land use of public type which is considered no-cost site, the nearest site to the end of sewer, the farthest from building and have adequate access to two roads. While for site 2, its land use type is park that means there is a cost to build there and farther than site 1 considering the end of sewer and is as far as site 1 and have access to two roads. For site 3, its land use is private that makes it the last option to select, the farthest site to the end of sewer, very close to building and has no access to any road.

TABLE VI
THE ASSESSMENT OF THE PROPOSED SITES.

Site	Assessment
Site 1	High suitability
Site 2	Medium suitability
Site 3	Unsuitable

V. Conclusion

This paper proposed integration between fuzzy MCDM approach represented by the fuzzy AHP and GIS to select the best location for a wastewater lift station. A real world case study from El-Mahalla El-Kubra was selected. In the proposed model, an application was designed in visualbasic.net environment that adopt FAHP to calculate the weights of the criteria, and GIS functionality was used to extract the suitability map with the weights calculated.

As a result of the study, we find that the proposed model is practical and effective identifying suitable sites with respect to multiple criteria. The model uses fuzzy set theory instead of dealing with crisp numbers to imitate the real life situations.

In future research, we recommend to use different defuzzification methods like the CFCS method, the fuzzy mathematical programming method or the fuzzification of Saaty's method (the Lamda-Max method) to convert the TFN into crisp number. Also, we recommend applying this model on a more complex problem.

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