Overlay Weighted Model and Fuzzy Logic to Determine the Best Locations for Artificial Recharge of Groundwater in a Semi-Arid Area in Egypt

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Abstract
In arid and semi-arid regions, where water scarcity is almost endemic, artificial recharge of groundwater is one of the most effective techniques for the augmentation of groundwater resources. The overlay weighted models using ArcGIS is one the most common techniques for creating a suitability map for the best locations of artificial recharge, however such models usually come up with wide prioritized areas. In this study a new approach, Fuzzy logic, was applied too to give more accurate suggestions by giving another classification inside each area of priority. Thematic layers were prepared from some maps and satellite images by the remote sensing techniques for a semi arid area in the western Nile delta in Egypt. These layers were classified, weighted and integrated in ArcGIS environment and by the means of the overlay weighted model a suitability map which is classified into number of priority zones was obtained. Numbers of points from different locations in each priority zone in the suitability map were selected to be manipulated by fuzzy logic in Matlab. It was found that fuzzy logic results give the same classification of the priority zones; moreover fuzzy logic could give more priority classification for the selected points in each zone.

***Key words*: semi-arid, artificial recharge, groundwater, overlay weighted model, ArcGIS, Fuzzy logic, remote sensing, Matlab.**

1. INTRODUCTION

Since the early eighties, the private sectors in Egypt have started to reclaim the western fringes of the Nile Delta region depending mainly on the groundwater resources. The reclamation process was accelerated during the eighties and up till now (Wassef, 2011). The total groundwater abstraction was 870 million m^3/year by the year 2000 and increased to more than one billion m^3/year in 2007 (The World Bank, 2007). The groundwater table started to decline due to the unplanned groundwater abstraction, and over pumping from production wells while the aquifers receive little or no replenishment particularly during the last decades because of the scarcity in the rainfalls, (Ghaly, 2001). Accordingly, the ministry of water resources and irrigation in Egypt initiated the main objective of finding out some other non conventional fresh water resources; hence special attention has been paid to artificial groundwater recharge in the arid and semi-arid regions. Artificial recharge is an effective technique for the augmentation of groundwater resources. A variety of methods have been developed to recharge groundwater, and most use variations or combinations of direct-surface, direct sub-surface, or indirect recharge techniques (Aish, 2004). The advantage of the direct-surface techniques lies in the ability to replenish underground water supplies in the vicinity of metropolitan and agricultural areas, where the groundwater overdraft is severe; and there is an added benefit from the filtering effect of soils and the transmission of water through the aquifer (Asano, 1985) and (Bouwer, 1978). Direct surface techniques are suggested here in this study, as the soil of the study area, Sadat City, has a good permeability and a wide area for implementation. The treated waste water from the existed treatment plants in the north of the city, where the oxidation ponds are, is going to be the source of the recharging water. The main objective of this study is the determination of the best locations for artificial recharge of groundwater in such semi-arid area by applying two approaches, the overlay weighted model by using ArcGIS and remote sensing techniques and the principles of the fuzzy logic.

2. THE STUDY AREA

The selected study area is Sadat City which is located between 30° 21´ E and 30° 41´ E longitude and 30° 19´ N and 30° 34´ N Latitude and it lies at the kilometer 93 on Cairo – Alexandria highway north-west of Cairo, its total area is 523.5 km^2, see Figure 1. Sadat City is a relatively new industrial city in the western desert and west to the Nile Delta in Egypt. Sadat city is the second city of the first generation which the agency of inhabitant communities built in 1976, in order to be a new inhabitant community. This city is based upon the industrial and agricultural activities. Its unique location between Cairo (The capital) and Alexandria (one of the biggest ports on the Mediterranean Sea), along the Delta, has made it a big centre to attract the local and foreign investments to form a large urban community. The total inhabitant area is 18 km^2, this area is divided into 12 parts with about 100,000 persons and it includes 5 industrial areas. The city is surrounded by a green area of 126 km^2; this made the international health organization classified it as one of the best ten industrial cities in the Middle East, because of its clean environment. The new city, as mentioned before, included several activities within it, figure 2 shows the Land use and the groundwater flow directions from the north into the south. All these activities are mainly depending on the groundwater; most of the supplying wells were constructed near to the residential parts of the city to cover the city needs for water, in addition to some other private wells which are used for irrigation purposes. Several studies have been done by The Research Institute of Groundwater in El Kanater-Egypt (RIGW) to find out the recharge distribution in the city, it was noticed that most of the city gets very little amount of water recharge or subsurface drainage which comes mainly from the green areas irrigation. The average recharge for the groundwater in the green areas is about 0.5 mm/day (RIGW, 2002).

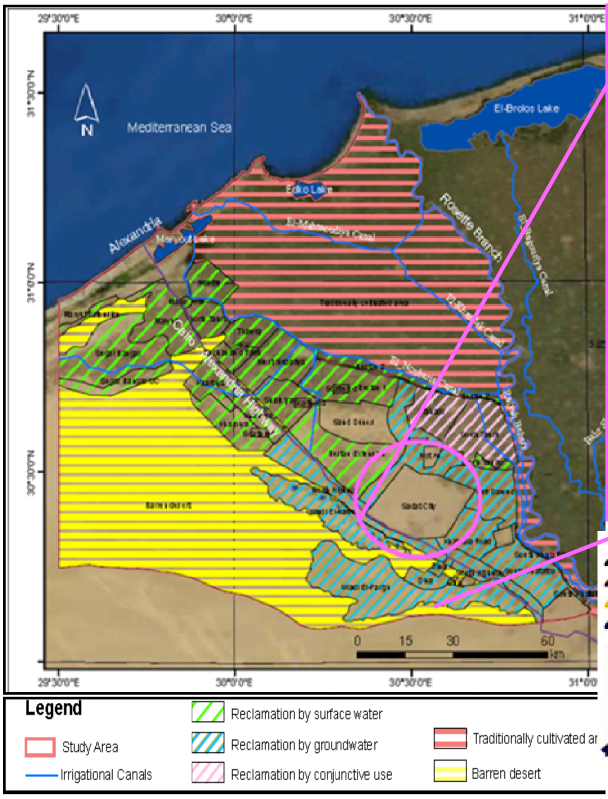

Figure 1: The study area location

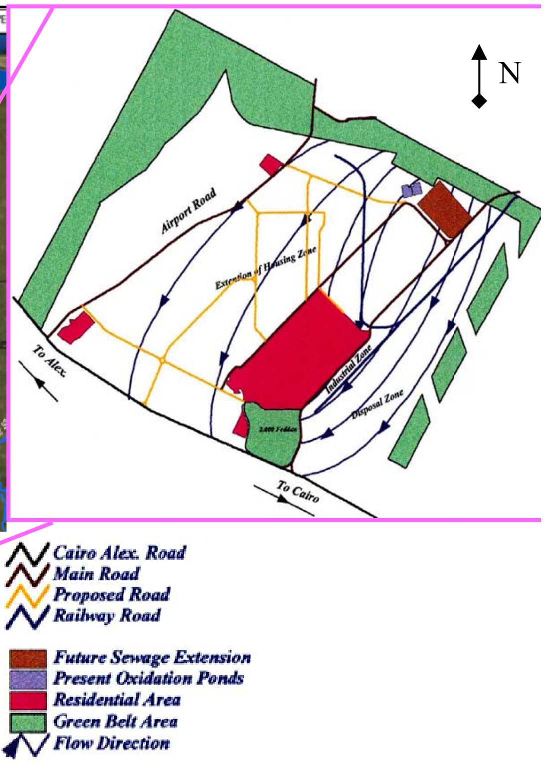

Figure 2: Sadat City Land use and groundwater flow directions

3. WEIGHTED OVERLAY SUITABILITY MODEL

A "Weighted Suitability Model" is developed using GIS techniques depending on a number of thematic layers (Omran, 2008) and ArcGIS Desktop 9.3 Manual. Such models are used for applying a common measurement scale of values to diverse and dissimilar inputs in order to create an integrated analysis. Additionally, the factors of the analysis may not be equally important. Each individual raster cell is reclassified into units of suitability and then multiply them by a weight to assign relative importance to each and finally add them together for the final weight to obtain a suitability value for every location on the map, this can be interpreted by equation 1 (Eastman, 2001).

$$S= \Sigma\, w_i\, x_i \qquad (1)$$

Where,
w_i = The weight of ith factor map
x_i = Criteria score of class of factor i
S = Suitability index for each pixel in the map

In the present study, all the thematic layers were integrated in ArcGIS 9.3 platform in order to prepare a map depicting suitable areas for artificial groundwater recharge. The total weights of each pixel of the final integrated layer were derived from the following equation;

$$S= (SL_f\, SL_c + LU_f\, LU_c + LW_f\, LW_c + LT_f\, LT_c + LR_f\, LR_c + L_f\, L_c + PR_f\, PR_c + DG_f\, DG_c) \qquad (2)$$

Where, S is the dimensionless artificial groundwater recharge index for each pixel in the final integration layer, SL is Land slope, LU is distance to the urban (residential) areas, LW is the distance to the supply wells, LT is the distance to the treatment plants, LR is the distance to the roads, L is the land use, PR is the pollution risk and DG is depth to groundwater. The subscript letter ‘f’ represents the weight of each factor, while ‘c’ represents the weight of each class of the individual factor (Chowdhury et al, 2006).

3.1 The Conceptual Model Steps to Create A Suitability Map

In this study, the main thematic layers are generated as an input for selecting suitable sites for a recharge project. A number of processes were performed to prepare these layers for being used as an input in an overlay weighted model. The following sections are going through the main steps which have been done.

3.1.1 The input dataset and the process

To model the spatial problem a schematic diagram was drawn for the study objective, the affecting parameters, the input datasets needed to reach the study goals and the process followed, see figure (3).

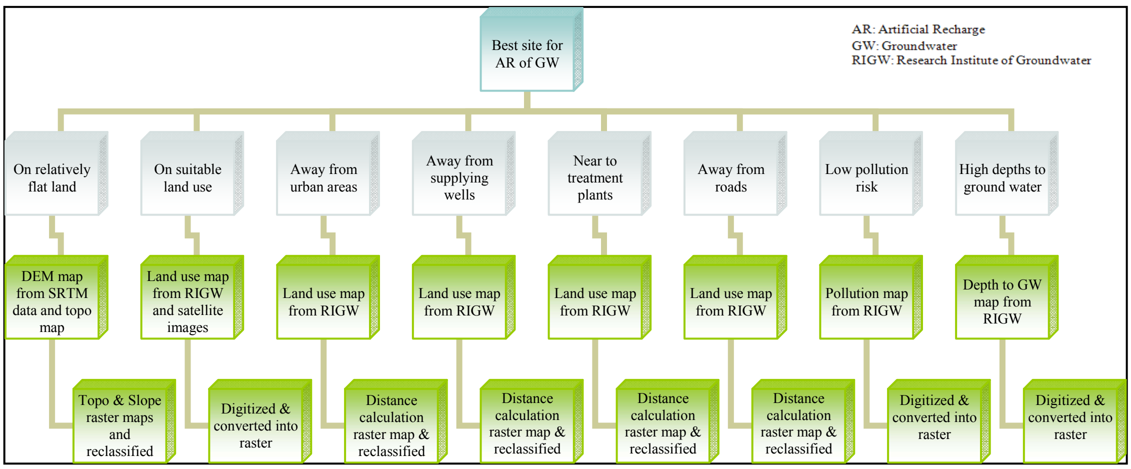

Figure 3: The input dataset and the process

As shown from Figure 3 there are 8 parameters have been selected to be thematic layers for the overlay weighted model analysis. Each parameter has some classifications and corresponding weight values which affect the model final decision, for more details refer to section 3.1.6. The kind of the soil and its structures were not taken into consideration because it was noticed from some borehole results which were carried out by the RIGW that all the city has the same kind of the soil and the same structure with some small differences in the depths between the northern parts and the southern parts of the city.

3.1.2 Remote sensing and DEM maps

Digital images of Landsat-7 satellite ETM+ sensor with a high resolution (23 m) were used. These images were downloaded from the Earth Science Data Interface (ESDI) at the Global Land Cover Facility and opened on ERDAS Imagine 8.5 and saved as one compiled imagine (*.Img) file to be imported to ArcGIS Environment with correct georeference. This map was used as a reference for all the next maps. As it was shown in the input dataset diagram the slope map was needed to find out the flat areas in the city, so digital elevation maps (DEM) from SRTM data for western Delta were downloaded (USGS, 2006).

3.1.3 Thematic layers for ArcGIS analysis

After adding the DEM and its data to ArcGIS platform the topographic and the slope maps could be generated by the use of the spatial analyst tools, then the study area was clipped according to its known coordinates see figures (4, 5).

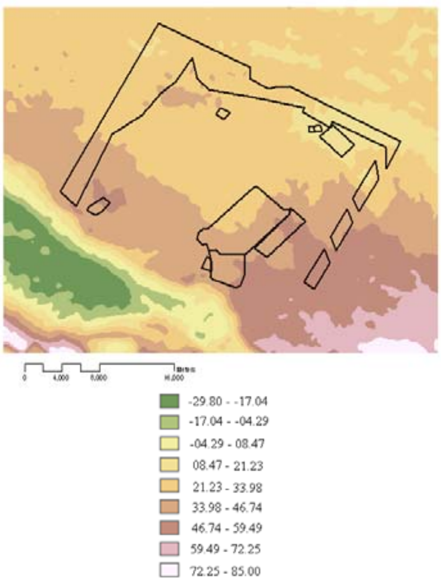

Figure 4: Topographic map for the study area

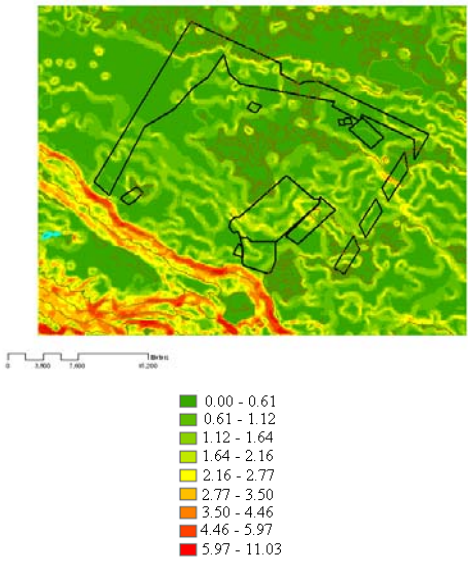

Figure 5: The slope map in degrees

Three maps (land use, pollution risk and depth to groundwater) for the city were obtained from previous researches (RIGW, 2002) and they were added to ArcGIS and georeferenced with the first reference map, then they have been Digitized and converted into raster maps, figures (6 to 9).

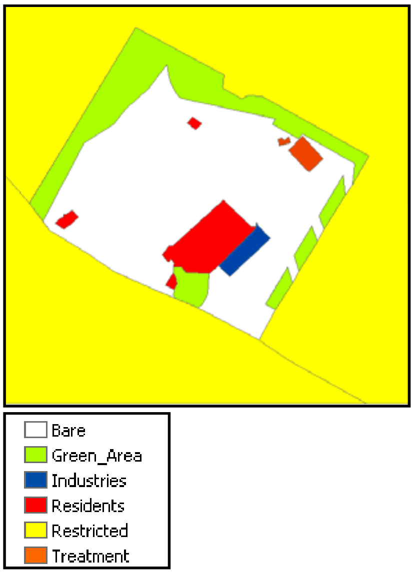

Figure 6: Sadat City land use map after being digitized on ArcGIS

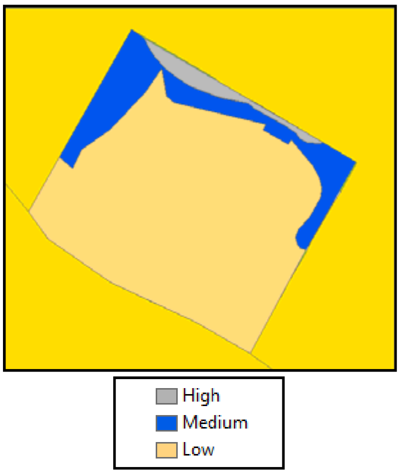

Figure 7: Pollution risk map on ArcGIS

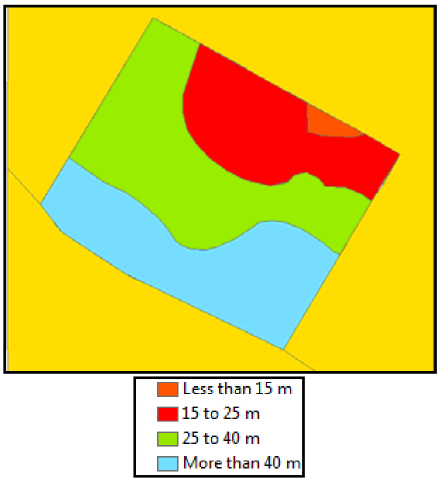

Figure 8: Depths to groundwater map on ArcGIS

3.1.4 Distances maps

As the study work diagram in Figure 3 showed that the distances to roads, urban areas, production wells and treatment plants are ones of the eight affecting parameters in determining the artificial recharge locations, these maps have been generated by using the Spatial Analyst Straight Line Distance function in ArcGIS which creates such maps by calculating the straight line (Euclidean) distance from the main objective site (in this case; roads, urban areas, production wells and treatment plants). The result is a raster dataset in which every cell represents the distance to the main objective site in meters. Figure 10 is an example for distances to roads.

3.1.5 Reclassifying the distances maps

All the distances maps have been reclassified to integer values instead of ranges to be used as inputs in the weighted model. To reclassify these maps the reclassify function was applied. A value of 10 was assigned to the most suitable range and 1 to the least suitable range. All the layers should have the same range of classes (1 to 10). Figure (11) shows an example for the reclassified map of distances to roads.

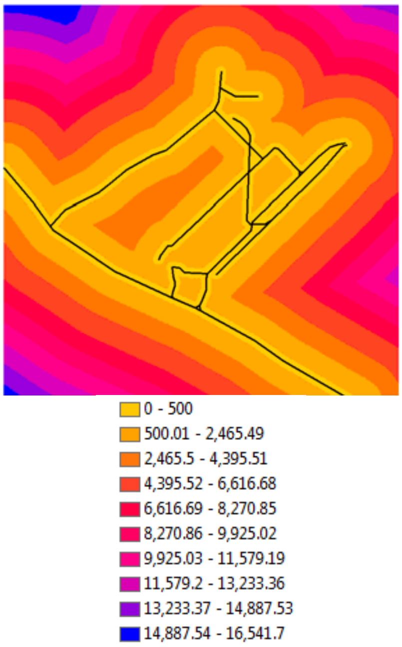

Figure 10: Distances to roads map in meters

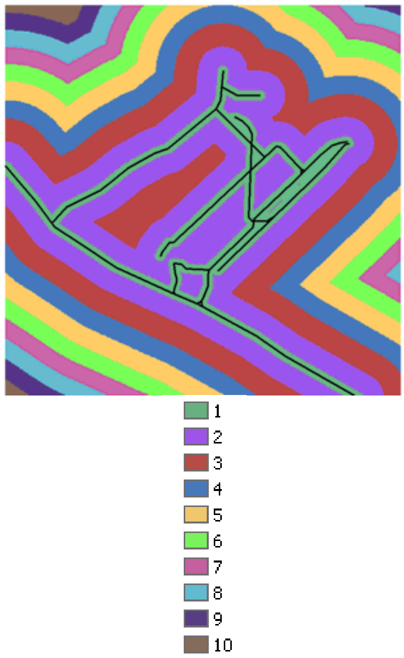

Figure 11: Reclassified distance to roads

3.1.6 Weighted Indexing table

Each raster is assigned a percentage influence according to its importance. The weight is a relative percentage, and the sum of the % influence weights must add up to 100. Each cell value is multiplied by their percentage influence then added to create the output raster. A weighted indexing table has been adopted to suggest the ideal location for artificial recharge using the eight parameters, as shown in Table 1. The weights in the present study were given upon the experience of other specialists from previous studies and upon the economic point of view (Elbeih, 2007), so in this research all the affecting factors were given an equal weight = 10 % except only the distance to treatment plant and the land use which were given weights equal to 20 %, because it is expected that the source of the water for the artificial recharge of groundwater in this city will be provided from the treated waste water from the treatment plants, so it is preferable and costly effective if these recharge areas are close to the treatment plants, moreover it is preferable to have these projects in bare lands more than agricultural areas or others not to affect the going on investments.

Table 1: A weighted indexing table

No.	Input Raster	Field	category	class	Influence weight %
1	Slope (S)	Very steep	Very Poor	1	10
		Flat	Excellent	10	
2	Dist. to Urban (LU)	Very close	Very Poor	1	10
		Farthest	Excellent	10	
3	Dist. to production wells (LW)	Very close	Very Poor	1	10
		Farthest	Excellent	10	
4	Dist. to Treatment Plants (LT)	Farthest	Very Poor	1	20
		Very close	Excellent	10	
5	Dist. to Roads (LR)	Very close	Very Poor	1	10
		Farthest	Excellent	10	
6	Landuse (L)	Green Area	Very Poor	1	20
		Residents	Poor	2	
		Industries	Quite good	3	
		Treatment	Very good	6	
		Bare	Excellent	10	
7	Pollution Risk (PR)	High	Very Poor	1	10
		Medium	Poor	6	
		Low	Excellent	10	
8	Depth to GW (DG)	Less than 15 m	Very Poor	1	10
		15 to 25 m	Poor	6	
		25 to 40 m	Very good	8	
		Larger than 40 m	Excellent	10	

Total =100 %

3.1.7 Suitable recharge locations

After preparing all the thematic layers and the table of weights which were needed for the weighted model, the weighted model could be built and run on ArcGIS, this came up with the most favorable sites selected using the previously mentioned criteria as shown in figure 12. The final integrated layer was classified from excellent to not suitable based on the weights assigned to each criterion. Weight "10" represents excellent sites while weight "0" represents unsuitable sites or areas out of the research study. It can be observed that the most suitable zones for artificial recharge lie in bare lands, away from the urban areas and near to the treatment plants. This is due to the high weights assigned to proximity to the treatment plants and to the land use.

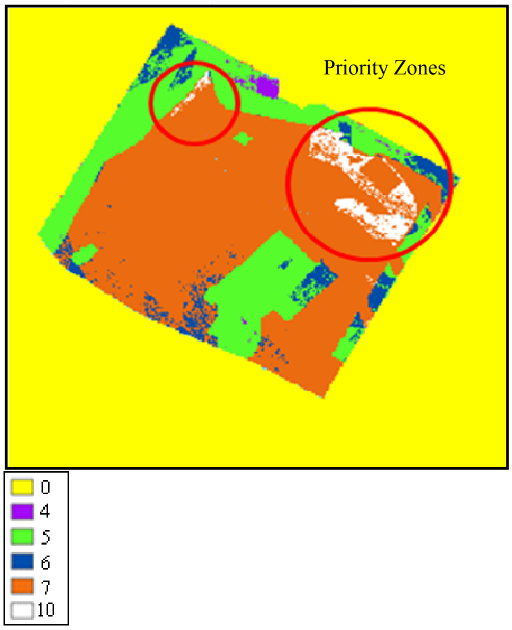

Figure 12: The suitability map

4. FUZZY INFERENCE METHOD

Fuzzy Logic is a form of algebra employing a range of values from "true" to "false" that is used in decision making with imprecise data, as in artificial intelligence systems. Fuzzy inference is the process of formulating the mapping from a given input to an output using fuzzy logic. The mapping then provides a basis from which decisions can be made. The used fuzzy inference system in this study is Mamdani-type (Mamdani, el al 1975) which could be applied by using Matlab 7. Mamdani's effort was based on Lotfi Zadeh's 1973 paper on fuzzy algorithms for complex systems and decision processes (Zadeh, 1973). Fuzzy inference process comprises of five parts: 1) fuzzification of the input variables, 2) application of the fuzzy operator (AND or OR) in the antecedent, 3) implication from the antecedent to the consequent, 4) aggregation of the consequents across the rules, and 5) defuzzification, see figure 13.

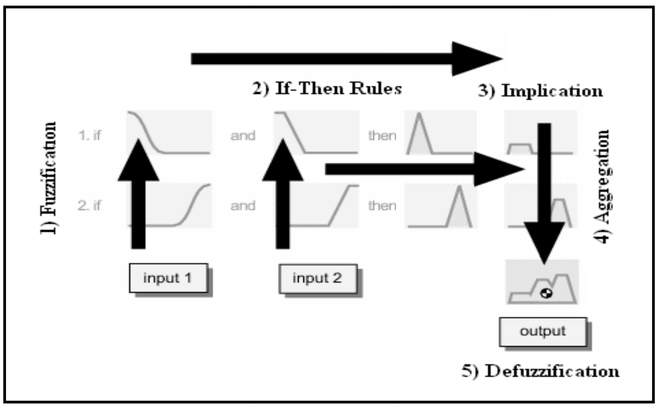

Figure 13: Fuzzy inference diagram, (Matlab Manual v.7.10, 2010)

4.1 Inputs Fuzzification (membership functions)

The first step was to take the inputs and determine the degree to which they belong to each of the appropriate fuzzy sets via membership functions. A *membership function* (MF) is a curve that defines how each point in the input space is mapped to a membership value between 0 and 1 (Ghayoumian et al., 2007). The input is always a numerical value limited to the universe of discourse of the input variable. In this study the inputs in cases of distances to road or treatment plants are limited between 0 and the farthest distance in these maps or 0 to 100 % in cases of Pollution risk, Depth to groundwater or Landuse and from 0 to 20° in case of the slope membership function. Figures (14 and 15) show two membership functions for two parameters. The only condition a membership function must really satisfy is that it must vary between 0 and 1 (on Y-axis). The function itself can be an arbitrary curve whose shape can be defined as a function that suits from the point of view of simplicity, convenience, speed, and efficiency. In this present study the triangle was selected for all the membership functions after several trials to find out the best functional shape.

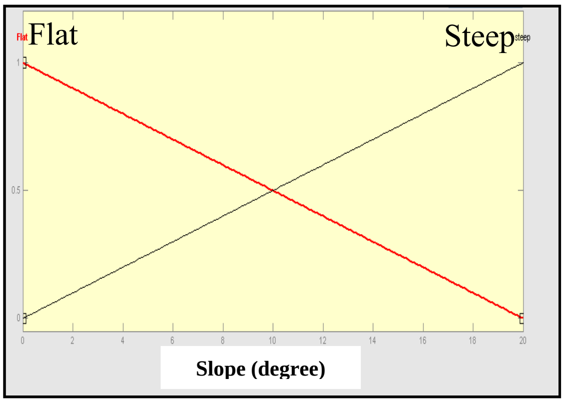

Figure 14: Slope membership function

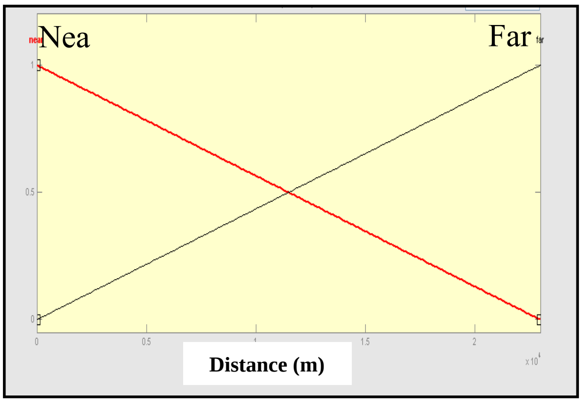

Figure 15: Distance to treatment membership

The main inputs here were the characteristics of 35 random selected points on the suitability map which were produced previously from the weighted model. These points were determined in a way to cover all the zones of priorities in that map and their characteristics are the values of the 8 affecting parameters at these points, figure (16).

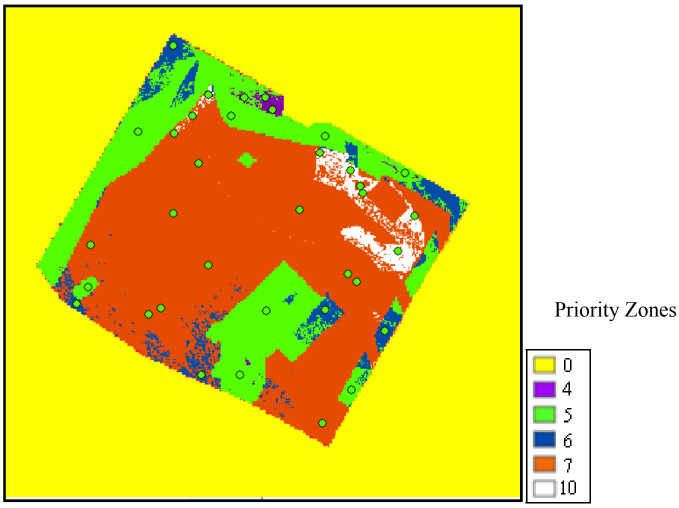

Figure 16: The selected points from the suitability map

4.2 If-Then Rules

After the inputs were fuzzified, If-Then rules have been assigned. The input to the fuzzy operator is two or more membership values from fuzzified input variables. The output is a single truth value, see figure (17) for the output membership functions (Poor, Good and Excellent). Fuzzy sets and fuzzy operators are the subjects and verbs of fuzzy logic. These if-then rule statements are used to formulate the conditional statements that comprise fuzzy logic. 112 rules (if-then) were assigned in this study, AND-minimum operator was used in all the rules, see table (2).

Table 2: All the possible used rules

		slope		Distance to road		Distance to urban		Distance to treatment		Distance to wells		Landuse		Pollution risk		Depth to GW	
		flat (Excellent)	steep (Poor)	near (Poor)	far (Excellent)	near (Poor)	far (Excellent)	near (Excellent)	far (Poor)	near (Poor)	far (Excellent)	Not Bare (Poor)	Bare (Excellent)	High (Poor)	Low (Excellent)	Low (Poor)	Deep (Excellent)
slope	flat (Excellent)			Poor	Excellent	Poor	Excellent	Excellent	Good	Good	Excellent	Poor	Excellent	Poor	Excellent	Poor	Excellent
	steep (Poor)			Poor	Good	Poor	Good	Good	Poor	Poor	Good	Poor	Good	Poor	Good	Poor	Good
Distance to road	near (Poor)					Poor	Good	Good	Poor	Poor	Good	Poor	Good	Poor	Good	Poor	Good
	far (Excellent)					Poor	Excellent	Excellent	Poor	Poor	Excellent	Poor	Excellent	Poor	Excellent	Good	Excellent
Distance to urban	near (Poor)							Good	Poor	Poor	Good	Poor	Good	Poor	Good	Poor	Good
	far (Excellent)							Excellent	Poor	Poor	Excellent	Good	Excellent	Poor	Excellent	Poor	Excellent
Distance to treatment	near (Excellent)									Poor	Excellent	Good	Excellent	Poor	Excellent	Good	Excellent
	far (Poor)									Poor	Good	Poor	Good	Poor	Good	Poor	Good
Distance to wells	near (Poor)											Poor	Poor	Poor	Poor	Poor	Good
	far (Excellent)											Good	Excellent	Poor	Excellent	Good	Excellent
Landuse	Not Bare (Poor)													Poor	Good	Poor	Good
	Bare (Excellent)													Poor	Excellent	Good	Excellent
Pollution risk	High (Poor)															Poor	Poor
	Low (Excellent)															Good	Excellent
Depth to GW	Low (Poor)																
	Deep (Excellent)																

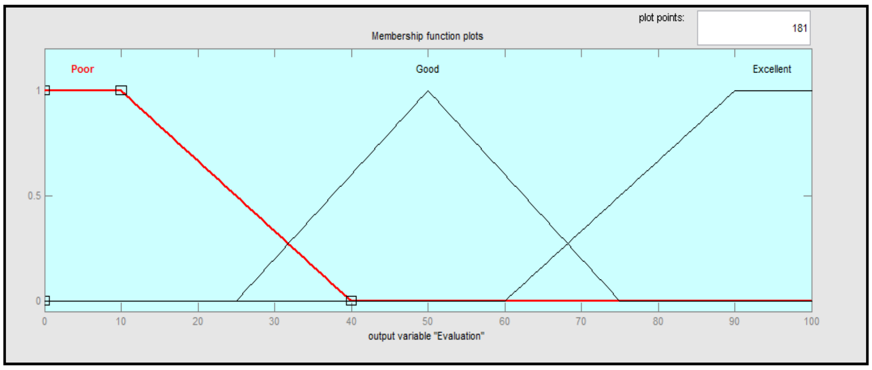

Figure 17: The output membership functions

4.3 Implication Method

The input for the implication process is a single number given by the antecedent, and the output is a fuzzy set. Implication is implemented for each rule. The consequent is reshaped using a function associated with the antecedent (a single number).The used implication method in the present study is AND method: *min* (minimum), which truncates the output fuzzy set. Figure (18) shows the used Implication method.

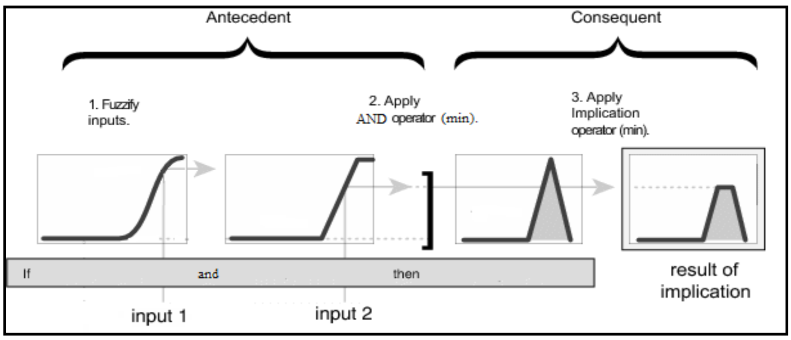

Figure 18: The used implication method, (Matlab Manual v.7.10, 2010)

4.4 The Outputs Aggregation

Aggregation is the process by which the fuzzy sets that represent the outputs of each rule are combined into a single fuzzy set. Aggregation only occurs once for each output variable, just prior to the fifth and final step, defuzzification. The used aggregation method here is SUM which is simply the sum of each rule's output set.

4.5 Defuzzification

The input for the defuzzification process is a fuzzy set (the aggregate output fuzzy set) and the output is a single number. The most popular defuzzification method and which was applied here is the centroid calculation, which returns the center of area under the curve. As a numerical example for the final calculations figure (19) represents the output evaluation surface viewer of a point at which 6 parameters values are kept constants while the slope and the distance to roads are variables. The viewer shows that best evaluation for this point to be a position for the project is achieved when the slope is very flat and the distance to the road is too far.

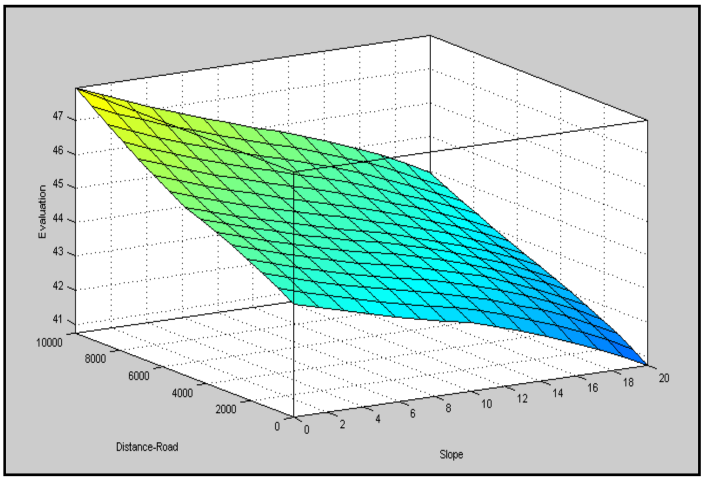

Figure 19: The surface viewer for a point in zone 10

Figure (20) presents the final evaluation results for the 35 selected points. The graph shows a strong agreement between the fuzzy results and the ArcGIS results as it gives the highest values for the selected points in zone 10 then 7 then 6 and so on, in addition to that fuzzy system could give some more classifications in each zone. For example, in zone 10 points number 5 & 8 have the highest output evaluations which mean that these 2 locations are the best in zone 8.

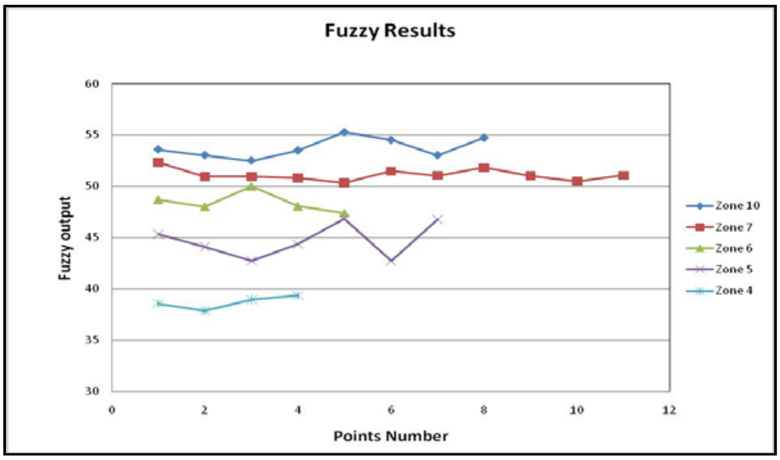

Figure 20: Fuzzy results for the selected points

5. CONCLUSION

- The best location for implementing this project is the northern part of the city near to the recharging water source, the treatment plants. This will provide the city with a new source of water for irrigation or industrial purposes according to the extracted water quality.
- Fuzzy logic gives the same classifications for each zone as the weighted models in ArcGIS, furthermore it could give more specific and accurate evaluation for the selected locations in each zone in ArcGIS.

6. RECOMMENDATIONS

- Overlay weighted models by ArcGIS can be used for determining the best areas in the study in general, however for more specific and accurate decisions fuzzy logic and field reconnaissance could be used after knowing the best areas from ArcGIS.
- Attribute table for all the pixels in the suitability map of ArcGIS could be exported, hence all the pixels characteristics could be used as an Input for Fuzzy and more accurate results could be obtained for the entire map.
- Once the best locations were determined from any spatial analysis, the results should be verified by carrying out a field reconnaissance before constructing the project.
- After taking a final decision about the project place a numerical model, like MODFLOW or FEFLOW, should be carried out to determine the amounts of recharged water which do not affect, negatively, the native groundwater and to determine the suitable residence time in the soil for the natural purification, so the places of water withdrawal can be also determined.
- Creating a water quality monitoring network after the project implementation to follow up the recharged water influences.

7. ACKNOWLEDGEMENT

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