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Land use suitability analysis for irrigation development using GIS-based fuzzy multicriteria evaluation procedure: a case study of Karkheh River basin in Iran

Ahmad Abrishamchi[1], Morteza Tasbandi[1], Massoud Tajrishy[1],

Miguel Marino[2], Ali Abrishamchi[2]

ABSTRACT: Land use suitability mapping and analysis is one of the most useful applications of GIS for spatial water and land planning and management. The analysis can specifically aim at identifying the most appropriate spatial pattern for irrigation and supplementary irrigation development in a basin according to specific requirements and preferences. In this context, a GIS-based multicriteria evaluation procedure is a useful approach because of its demonstrated ability to integrate multiple criteria, preferences of different groups, expert knowledge, and with-standing spatial; non-spatial and inexplicit data sources. It involves evaluation of the criteria ranging from soil, terrain, water availability, social and economic. Many of these factors are vaguely defined and characterized by their inherent vagueness. Multicriteria decision-making techniques like ranking, rating etc. are employed for suitability analysis. As this process incorporates expert knowledge and judgment by decision makers at various levels, it is very much subjective in nature. Although techniques like Analytic Hierarchy Process (AHP) incorporate experts' knowledge but fails to address the inherent uncertainty in them. This paper focuses on addressing uncertainty in the process of land suitability analysis for irrigation development in a Geographical Information System (GIS) environment using two approaches; AHP and Fuzzy AHP. It is found that Fuzzy AHP performs better than AHP technique. As the process of decision making involves a range of criteria and good amount of expert knowledge and judgments, these factors greatly influence the outcomes. The ability of two techniques to model the sensitivity of decision-making process is investigated. Alpha cut and lambda values provide and facilitate good sensitivity analysis. Two methodologies are implemented to analyze the suitability of lands for irrigation development in Qaresoo Sub-Basin of Karkheh River Basin in Iran.
KEY TERMS: Multi-criteria Decision Making, Analytic Hierarchy Process, Fuzzy AHP, Geographical Information System, Alpha cut, Lambda Function.

1. INTRODUCTION

The industrial revolution of nineteenth and twentieth century has permanently altered the pattern of human development and rates of consumption of the world's resources (Blowers, 1996). Similar to any other resource management tasks, land resource planning also involves specialized resource allocation problem and the challenge is to formulate complex, spatially and temporally interdependent patterns of uses to achieve multiple, non-commensurable and frequently conflicting goals. Solving problems and making decisions about the sustainable use of water and land resources demand for integration of data and knowledge from a wide spectrum of disciplines.

A systematic approach to decision analysis is required to improve the quality of the decisions and to justify the actions to be taken. Advances in the field of Geographical Information Systems (GIS) provided vast amount of raw data in the form of resource inventory and mapping. However to be useful for decision making the data need to be processed to obtain relevant information. Broadly two types of information are associated with the spatial decision making process: geographical information and information about the decision maker's preferences. In this regard a framework that integrates the GIS capabilities of Multicriteria Decision Making (MCDM) techniques for aggregating the geographical data and the decision maker's preference shows immense potential to address spatial decision making problems (Malczewski, 1999). Such integration improves the effectiveness of decision-making by incorporating decision maker's judgments and computer based programmes within the decision making process.

[1] Professor, Graduate Student, and Associate Professor, respectively, Department of Civil Engineering, Sharif University of Technology, Tehran, Iran

[2]Professor and Ph.D. Student, respectively, Department of Civil and Environmental Engineering, University of California, Davis, Ca.

1.1. LAND SUITABILITY ANALYSIS

Land suitability is the ability of a given type of land to support a defined use. The process of land suitability classification is the evaluation and grouping of specific areas of land in terms of their suitability for a defined use. The main objective of the land evaluation is the prediction of the inherent capacity of a land unit to support a specific land use for a long period of time without deterioration, in order to minimize the socio-economic costs. Land suitability analysis is an interdisciplinary approach by including the information from different fields like soil science, social science, environmental science, economic and management. Being interdisciplinary, land suitability analysis deals with information, which is measured in different scales like ordinal, nominal, ratio scale etc. Based on the scope of suitability, current research aims at developing a methodology to analyse the current suitability using fuzzy logic.

1.2. FUZZY SET THEORY

Fuzzy logic methodologies may provide a scheme for the representation and manipulation of the uncertainty, which is related to the classification of individual locations according to their attribute values. It implements classes or groupings of data with boundaries that are not sharply defined.

For multi-criteria evaluation, Saaty's Analytic Hierarchy Process (AHP) is used to determine the weights of each individual criterion (Saaty, 1980). AHP is a mathematical method to determine priority of the criteria in the decision making process. It is a popular tool used by decision makers in multi-attribute decisions.

1.3. ANALYTICAL HIERARCHY PROCESS (AHP)

AHP is a multi-criteria decision method that uses hierarchical structures to represent a problem and then develop priorities for alternatives based on the judgment of the user (Saaty, 1980). Saaty has shown that weighting activities in multi-criteria decision-making can be effectively dealt with via hierarchical structuring and pairwise comparisons. Pairwise comparisons are based on forming judgments between two particular elements rather than attempting to prioritize an entire list of elements (Saaty, 1980). The AHP scales or pairwise comparisons are presented in Table 1.

Table 1. The AHP scales for paired comparisons.

Intensity of importance	Definition and explanation
1	Equal importance-Two activities contribute equally to the objective.
3	Moderate importance-Experience and judgment slightly favor one activity over another.
5	Strong importance-Experience and judgment strongly favor one activity over another.
7	Demonstrated importance-An activity is strongly favored and its dominance is demonstrated in practice.
9	Extreme importance-The evidence favoring one activity over another is of the highest possible order of affirmation.
2-4-6-8	Intermediate values between the two adjacent judgments when compromise is needed.

Based on this AHP method, design a spreadsheet package called EXPERT CHOICE and it is used in calculating weight for each layer. It has an ability to calculate weights, for multiple criteria with pairwise comparisons.

2. SURVEY ON FUZZY DECISION MAKING

Saaty's AHP is first extended by Van Laarhoven and Pedrycz (1983). They use triangular fuzzy numbers for fuzzification of the pairwise comparison matrix. Later Buckly (1985) proposed some modifications over that where the normal equations is used to replace the fuzzy pairwise comparison ratios. Buckly (1985) also proposes the use of trapezoidal fuzzy numbers instead of triangular fuzzy numbers by criticizing that the algebraic operations on triangular fuzzy numbers do

not necessarily produce triangular fuzzy numbers, in order to preserve the triangular shape of the numbers Van Laarhoven and Pedrycz (1983) are forced to employ approximate methods. Later, Boender et al. (1989) presented a modified method over Van Laarhoven and Pedrycz's method by criticizing the normalization procedure they followed to minimize the regression equation. These methods involve complex process of comparison and ranking of fuzzy utilities and may produce unreliable results.

Deng (1999) proposes an outstanding method for multicriteria analysis that involves no complex calculations, which can be applied effectively for the problems involving qualitative information. He introduces α-cut analysis to avoid complex comparison of fuzzy utilities. This method is well designed to address all sorts of uncertainties. α-cut analysis allows to incorporate ambiguity in expert knowledge and the optimism index (λ) to address the decision makers attitude.

However, these methods derive priorities from the Pairwise Comparison Matrix (PCM) constructed usin triangular fuzzy numbers. This Fuzzy PCM constructed using triangular fuzzy numbers will lead to some inaccuracies (Mikhailov, 2003). He states that triangular fuzzy numbers are not always symmetric, and this skewness in reciprocals leads to the well-known phenomenon, the rank reversal. The calculation involved with this technique is complicated and time consuming.

3. RESEARCH OBJECTIVE

The aim of this research is to explore the role of fuzzy logic in multi-criteria evaluation of land use suitability for irrigation development. Specific objective is to develop multi-criteria decision making technique using fuzzy logic for land use suitability analysis for irrigation development in Qaresoo subbasin of Karkheh river basin, Iran.

4. THE STUDY AREA

The study area is Qaresoo, a sub basin in the Karkheh river basin, Iran (Figure 1). The area located between latitude 34° 20'N and 34° 53'N and longitude 46° 22'E and 47° 22'E. The watershed area is 5493.6 km^2. Around 52% of the area is mountains and the rest are plains. The study is limited to plains of the sub-basin area because of intensive erosion in mountains.

The total population in agricultural areas of this sub-basin is estimated to be around 176500. In the study area the road accessibility is reasonably good. This area has five major cities that are: Kermanshah, Robat, Ravansar, Halshi and Kamyaran. The soil texture of lands in the area is heavy and the soil type in most lands is clay. The altitude varying between 1300 to 3351 m above MSL and the mean slope of the study area is 14.2%. Wheat is the principle crop of this area. Qaresoo sub-basin has three perennial rivers: Qaresoo, Merk and Ravansar. The rest of rivers are seasonal. There is a tunnel in Ravansar city that its water would be transmitted to the lands in the study area.

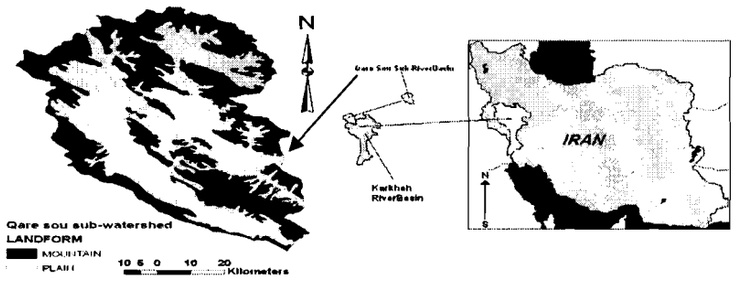

Figure 1. Location of the study area

5. METHODOLOGY

In the current study, the following two methods are applied for multi criteria evaluation:

- Analytic Hierarchy Process (AHP)
- Fuzzy AHP

Here, special emphasis is on the extended capabilities of the Fuzzy AHP for land use suitability analysis.

5.1. HIERARCHICAL ORGANISATION OF THE CRITERIA

Malczewski (1999) states that relationship between the objectives and attributes has a hierarchical structure. At the highest level one can distinguish the objectives and at lower levels, the attributes can be decomposed. Figure 2 shows the hierarchical structure used in this study. This structure has two extra lower levels that are not shown in Figure 2. These two levels are the attribute classes and alternatives, respectively. After dividing the study area to 57 zones by using a land evaluation map of the study area, our alternatives would be these zones. We specified classes for attributes and those criteria that had not attributes in the structure. For naming these classes, we used linguistic variables.

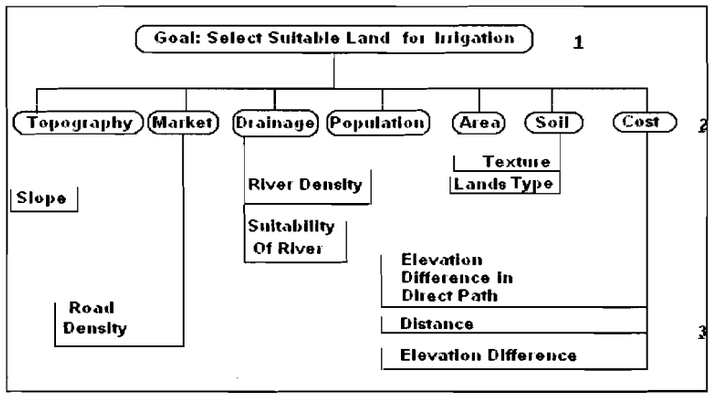

Figure 2. Hierarchical organization of the criteria considered for the study

5.2. ANALYTIC HIERARCHY PROCESS (AHP)

In this study, we used Rating Model because the number of alternatives exceeds 9. The fundamental input for the AHP is the pairwise comparison matrix, which gives answers to a series of questions like "How important is criterion A relative to criterion B?" In AHP, comparisons are used to establish both weights for criteria and preference scores for classes on different criteria. The comparisons are measured on a ratio scale. First, a decision-maker has to make comparison between each element under evaluation. Here, the comparisons are made qualitatively, for example weak preference, moderate preference etc., and are termed as Pairwise Comparisons (PCs). Later, these preferences are converted to quantitative values using the scale designed by Saaty (1980), (Table 1). By using an EXPERT CHOICE software, we can calculate the overall weights of zones.

5.3. FUZZY AHP

Inputs for the fuzzy AHP approach are the crisp PCMs. The crisp PCMs are fuzzified using the triangular membership functions (Table 2). The PCMs constructed by the comparison among criteria in a group in the hierarchy are fuzzified to obtain fuzzy performances per criteria by using the Row Sum approach. The fuzzy performances for criteria are multiplied with the fuzzy performances for classes. The multiplication is executed over the hierarchy up to the first level. In the last stage, these performances are processed with alpha cut analysis and lambda functions. To obtain an interval performance

Table 2. Conversion of crisp PCM to fuzzy PCM

Crisp PCM value	*Fuzzy PCM value*	*Crisp PCM value*	*Fuzzy PCM value*
1	(1,1,1), if diagonal (1, 1, 3), otherwise	1/1	(1/1, 1/1, 1/1), if diagonal (1/3, 1,1), otherwise
2	(1, 2, 4)	1/2	(1/4,1/2, 1/1)
3	(1, 3, 5)	1/3	(1/5,1/3, 1/1)
5	(3, 5, 7)	1/5	(1/7, 1/5, 1/3)
7	(5, 7, 9)	1/7	(1/9, 1/7, 1/5)
9	(7, 9, 11)	1/9	(1/11, 1/9, 1/7)

matrix, we apply the α-cut over these fuzzy numbers. Now the crisp performance matrix is obtained by applying the λ, the optimism index. In land use suitability study this function is used to depict boundaries of suitability classes. Optimism index λ is applied over the interval performance set as shown below resulting in a crisp performance matrix C.

$$c_\lambda = \lambda * P_{r\alpha} + (1-\lambda) * P_{l\alpha} \qquad (1)$$

where $\lambda = [0, 1]$, $P_{r\alpha}$ and $P_{l\alpha}$ represent the right and left value of the interval set

6. SENSITIVITY ANALYSIS

To enlighten the effects of uncertainty in expert knowledge, we perform a sensitivity analysis on the fuzzy AHP technique. An alpha value of 0.6 and three different lambda values 0, 0.5 and 1 are used in this analysis. An alpha value of 0 indicates that the decision environment is highly uncertain and 1 indicates that the problem involves no uncertainty. Intermediate values indicate uncertainty between these two extreme ranges. Here, only one alpha value (0.6) is considered assuming that the decision environment is certain to some extent. This assumption is valid, because the criteria are measured with comparatively good accuracies by advance technology.

7. RESULTS

Evaluation criteria are framed and organized in a hierarchy, as shown in Figure 2. The results of two approaches are put together and discussed here. Based on the overall weights calculated by AHP method, suitability ranges were identified. Figure 3 shows suitable lands for irrigation development by AHP method.

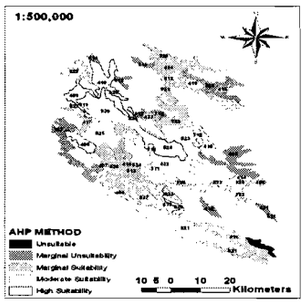

Figure 3. Suitable lands for irrigation by AHP method

Land use suitability of the study area is evaluated using AHP methodology. Accordingly 73% of the total available area is marginal to moderately suitable for irrigation development. Only one zone is unsuitable. The number of zones in high suitability class is 9.

Three different scenarios of land use suitability for irrigation development are obtained by applying lambda function for Fuzzy AHP method. These scenarios show how the uncertainties involved in land use suitability decision-making process will influence the outcomes of the process. Figure 4 shows the results obtained with lambda values 0, 0.5 and 1.

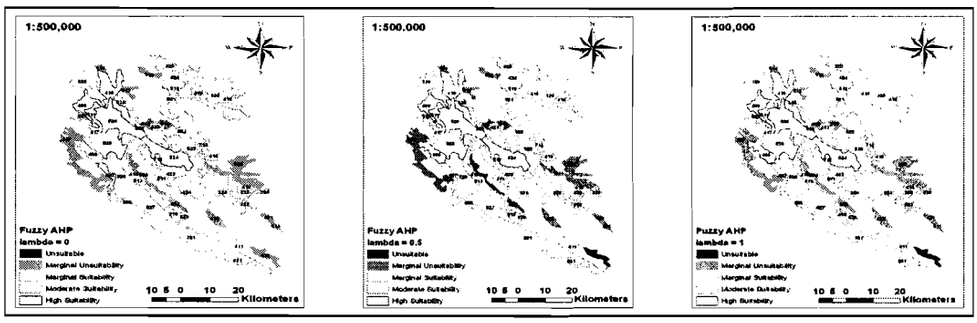

Figure 4. Land use suitability maps obtained with lambda values 0, 0.5 and 1 by Fuzzy AHP method

With $\lambda = 0$, the number of zones in moderate suitability class are 20. There is no zone in unsuitable class. Around 67% of the total available area is marginal to moderately suitable for irrigation development.

With $\lambda = 0.5$, high suitability class dominates over 20% of the area and moderately suitability class is restricted to the 35% of the area. The three lower suitability classes are squeezed down to a total of 45%. Here, it is noticeable that area under the class marginal suitability is increased in compare to $\lambda = 0$. It is visually interpretable, that there has been a shift from areas under class moderate suitability (at $\lambda = 0$) towards areas under class marginal suitability ($\lambda = 0.5$) (see figure 4).

With $\lambda = 1$, the number of zones is up to 19. There is a shift in number of zones under class marginal suitability (at $\lambda = 0.5$) towards class moderate suitability ($\lambda = 1$). The classes of high suitable, marginal unsuitable and unsuitable are no more sensitive for $\lambda > 0.5$. The expert knowledge is most uncertain in classes of marginal suitability and moderate suitability.

The results of the AHP approach are satisfactory. These results are comparable with that of the fuzzy AHP. Although AHP incorporates expert knowledge, it fails to incorporate the uncertainty involved in the expert knowledge, his judgment and opinions.

Fuzzy AHP gives considerably good results. The approach incorporates uncertainty of expert opinions, while comparing the criteria. Furthermore, this approach provides opportunity to incorporate uncertainty that might arise while expressing the preference over these criteria. The alpha cut and λ – values used in the calculation of the fuzzy performances incorporate the uncertainty of various kinds. Alpha cut is known to incorporate the experts or decision maker's confidence over his preference or the judgments. The λ – values address and measure the uncertainty involved in deciding upon the range of values obtained by alpha cut. The value would be near 1 if the expert or the decision maker is certain that the value of the criterion score is close to the maximum value of the uncertain range. The value would be near 0 if the decision maker is more certain that the value of the criteria score is close to the minimum value of the uncertain range.

8. CONCLUSIONS

The land use suitability evaluation involves the criteria, which are in different scales ranging from nominal to ratio. Many inputs into the GIS based land use suitability evaluation are the maps of the criteria, which are representing the complex, continuous and uncertain information in a simple, classified map with the crisp boundaries among them. The Boolean methodologies and other simple technique are used for the land use suitability evaluation, which aggravate outputs of the evaluation. In order to overcome these problems present research explores the capability of two approaches; AHP and Fuzzy AHP. It is found that Fuzzy AHP performs better than AHP technique. The suitability problem is structured to fit into the framework of decision-making. The criteria are organized in the hierarchy (Figure 2) to facilitate incorporation of expert knowledge from various disciplines. Keeping in mind the complexity of decision-making process the criteria are grouped at several stages over the hierarchy.

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