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Page: 27 - 35
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GIS-based Interval Pairwise Comparison Matrices as a Novel Approach for Optimizing an Analytical Hierarchy Process and Multiple Criteria Weighting

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Abstract

Multi-criteria decision analysis (MCDA) methods are used for criteria ranking/weighting in GIS environments, and. the analytical hierarchy process (AHP) is the most popular method for GIS-based MCDA. In this paper, a novel method is presented for optimizing pairwise comparison decision-making matrices in the AHP. The method is based on interval pairwise comparison matrices (IPCM). In order to assess the capability of the new approach, it was tested for landslide susceptibility mapping (LSM). To measure the improved accuracy achieved by the method, both AHP and IPCM were used for ranking nine causal criteria relating to landslide phenomena in Marand County, northwest Iran. The criteria weightings results were then used for LSM based on each of the methods. In order to validate the results, the outcomes of both methods were compared qualitatively against an existing landslide inventory dataset. The results of the evaluation indicated an improvement in accuracy of 3% in the LSM that was developed using the IPCM method. Our results will be important for researchers involved in GIS-based spatial decision-making problems, and for developing GIS-MCDA

Keywords:

interval pairwise comparison matrices, multi-criteria decision analysis, optimizing

1 Introduction

MCDA methods are effective techniques for GIS-based spatial decision making system (SDMS) (Feizizadeh and Blaschke, 2010). The integration of these methods with GIS spatial analysis provides a smarter methodology in spatial modelling approaches to identify more effective criteria for a SDMS (Mokarram and Hojati, 2016). However, all decision-making approaches involving natural systems face a number of uncertainties, ranging from ambiguity in defining problems and goals to uncertainty in data and models (Refsgaard et al., 2007). In addition, uncertainty in GIS-MCDA may come from various sources, such as uncertainty of the dataset, criteria weights or model parameters (Malczewski, 2006). Technically speaking, criteria weights are often the greatest contributor to controversy and uncertainty (Chen and

Zhu 2010; Feizizadeh and Blaschke 2012a). Even small changes in decision weights and methods may have a significant impact on the rank ordering of the criteria and accordingly the results of the GIS-MCDA, which can lead to inaccurate outcomes and undesirable consequences (Feizizadeh and Blaschke, 2014).

Within the GIS-MCDA methods, the AHP method has been applied to solve many SDMSs in the field of geosciences (Tiwari et al., 1999; Nekhay et al., 2008; Feizizadeh and Blaschkle, 2012b). However, it is criticized for some of its inadequacies. Since the pairwise comparisons of the AHP are based on experts' knowledge, it is prone to uncertainty, which leads to cognitive limitations of experts' subjective pairwise comparison processes (Ligmann-Zielinska and Jankowski, 2014; Feizizadeh et al., 2014a). Moreover, experts are sometimes incompletely aware of the nature of the criteria. Consequently, they may not be sure in their choice of a crisp number from 1 to 9 in order to compare the criteria in the pairwise comparison matrices (Benke et al., 2009; Xu and Zhang, 2013). In addition, not all experts will agree on a crisp number to compare two specific creations, and consequently they will rarely reach the same set of matrix elements for the pairwise comparison matrix (Chen and Zhu, 2010). To reduce the chance of error in GIS-MCDA methods, an uncertainty analysis is applied, a process that leads to the assessment of the quantative and qualitative reliability of the MCDA results (Feizizadeh and Blaschke 2014, Feizizadeh and Blaschke, 2012b). In order to minimize the uncertainties associated with the traditional AHP method, the technique must be flexible enough to use a full range of values for the pairwise comparisons. This makes it more practical for a variety of decisions and users (Liew and Sundaram, 2009). The primary purpose of this study was to introduce a new approach to deal with the uncertainty and inaccuracy in the AHP by using IPCM, which uses interval values for pairwise comparisons. This approach was then used as a GIS-based SDMS for landslide susceptibility mapping (LSM) in Marand County.

2 Study Area and criteria selection

The study area, Marand County, with a size of 3,286 km2, is located in northwest Iran. The area has five cities and more than 120 villages. Elevations in the County are between 900 m.a.s.l. and 3,125 m.a.s.l. Landslide is a natural hazard that causes considerable damage to public infrastructures, rural property, natural resources, and agricultural and industrial activities in northwest Iran, and in Marand County in particular (Feizizadeh and Haslaue, 2012; Feizizadeh et al., 2014b). In our research, nine causal criteria related to landslides were analysed for the LSM process: land use/cover, elevation, slope, aspect, distance to roads, distance to faults, distance to streams, geology and precipitation. Thematic and geometric editing, topological corrections, and simple basic calculations (e.g., buffer zones around roads and streams) were applied on the selected criteria when preparing them for inclusion in a spatial dataset. Accordingly, all criteria were included in the GIS environment as raster layers with a 30m resolution.

3 Methodology

Workflow for GIS-MCDA applied to LSM

Landslide susceptibility has been mapped in several areas around the world since the early 1980s (Rossi and Reichenbach, 2016). Researchers have used a variety of methods for landslide susceptibility evaluation and mapping, including analysis of landslide inventories and statistically based models (Guzzetti et al., 1999; Rossi and Reichenbach, 2016). In this study, we aim to map susceptibility to landslide through a novel multi-criteria approach. LSM is an efficient way to predict where landslides are likely to occur (Feizizadeh et al., 2014b). It also helps managers to identify landslide-susceptible areas and reduce the severe adverse effects of this hazard by appropriate slope management (Pradhan, 2011). A powerful multi-criteria approach and accurate input data (i.e. reliable maps) are required for modelling the areas in Marand County which are susceptible to landslides. In this study, a novel method was introduced that is an optimized form of the traditional AHP. Our methodology consists of three stages:

1. The criteria which relate to landslide phenomena were prepared as different GIS raster layers. Because each criterion has a distinct influence on landslide, each was weighted or ranked according to its influence (Dehghani et al., 2014), using the IPCM approach. In this approach, experts use interval values to compare criteria in the AHP's pairwise comparison matrices, and criteria were ranked through the weightings derived from IPCM.
2. A landslide susceptibility map was prepared using the weighted criteria from the results of the IPCM. The weighted GIS raster layers were combined with a weighted overlay method (Dehghani et al., 2014). In the resulting raster map, pixels are assigned values of between 0 and 100; the values which are close to 100 indicate a high risk of landslide (Figure 1).
3. Within the validation step, the accuracy of the results was tested against the known landslide dataset by applying the relative operating characteristics (ROC) technique.

Analytical hierarchy process (AHP)

The AHP is a common method for criteria-weighting that was developed by Saaty (1980). It involves three main steps: calculating the criteria weights, comparing alternatives for any criterion, and ranking the criteria based on their achieved weights (Qaddah and Abdelwahed, 2015). It structures a decision problem into a hierarchy system with a goal, decision criteria and alternatives. Experts can compare any two criteria (x_i and x_j) in a pairwise comparison matrix (Mikhailov, 2003). The AHP assesses the significance of one criterion relative to another in order to determine the criteria weights within the matrix. The values of the matrix are first converted to decimals, squared and standardized. Standardization is by arithmetic mean (Qaddah and Abdelwahed, 2015).

Interval pairwise comparison matrix (IPCM)

Although the AHP method provides a very popular process for decision making, most researchers believe that the judgments of experts play a fairly major role in the method: the results are greatly affected by expert opinion, which is therefore a source of significant uncertainty in the AHP method. To overcome this problem, the IPCM method was applied in this study. This method uses interval matrices rather than ordinary ones for the purpose of pairwise comparisons. The greatest advantage of the method is that it makes the AHP more flexible. Consequently, the AHP can deal with uncertainties which result from experts' judgments. Generally, it is more realistic if experts present their comparisons as an interval of x, in which $x = [l_{ij}, u_{ij}]$, rather than as a crisp number (Lan et al., 2009), where x shows that the criterion x_i is between l_{ij} and u_{ij} times as preferred as the criterion x_j, and all of these intervals are organized in an interval comparison matrix A:

$$A = \begin{bmatrix} 1 & [l_{12}, u_{12}] \cdots & [l_{n2}, u_{n2}] \\ [l_{21}, u_{21}] & 1 \quad \cdots & [l_{n2}, u_{n2}] \\ \vdots & \vdots \quad \vdots & \vdots \\ [l_{n1}, u_{n1}] & [l_{n2}, u_{n2}] \cdots & 1 \end{bmatrix} \qquad (1)$$

$$l_{ij} \leq u_{ij}, \forall i, j = 1,2, \dots, n \text{ and } l_{ij} \geq 0\,,\ u_{ij} \geq 0, \forall i, j = 1,2, \dots, n$$

This matrix is a reciprocal matrix as well as a definite comparison matrix. It is defined as:

$$l_{ij} = \frac{1}{u_{ji}}, u_{ij} = \frac{1}{l_{ji}}\ , \forall i, j = 1,2, \dots, n \qquad (2)$$

The method of calculating this matrix and analysing the consistency are broadly described by Ghorbanzadeh et al. (2017). The final result is a vector $w = (w_1, w_2, \dots, w_n)$, shown in Table 1.

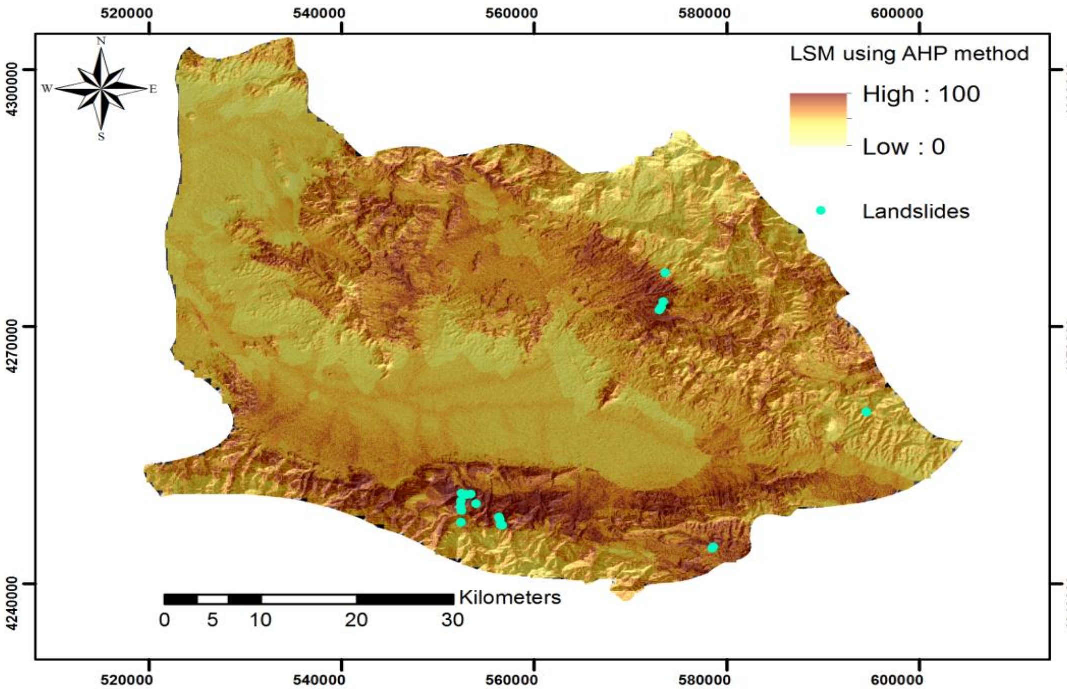
Table 1: Weights calculated for criteria based on the AHP and the IPCM methods

	Distance to stream	Slope	Land use/cover	Lithology	Aspect	precipitation	DEM	Distance to fault	Consistency ratio
IPCM Weights	0.086	0.185	0.080	0.130	0.140	0.100	0.159	0.120	0.037 & 0.040
AHP Weights	0.092	0.195	0.063	0.115	0.160	0.072	0.166	0.137	0.012

3 Results

In order to produce the landslide susceptibility (LS) maps, the derived weightings based on both methods were employed separately for data aggregation within a GIS environment. Figure 1 shows the maps for Marand County. In order to validate the results and measure the capability of the proposed approach for improving the accuracy of results, the derived maps were validated against the known landslide inventory dataset. In order to do this, the accuracy of the LS maps was evaluated by calculating their relative operating characteristics (ROCs), and a database including 20 known landslides in the study area was used. The ROCs plot the false positive rate on the X-axis and 1, and the false negative rate on the Y-axis. This indicates the trade-off between the two different rates (Biggerstaff, 2000; Akcapinar et al., 2011). Based on the theory of the ROC curve, the Area Under Curve (AUC) shows the accuracy of a prediction. The best result is for a value close to 1.0 (Fawcett, 2006; Nandi and Shakoor, 2009; Feizizadeh et al., 2014b). The results from the ROC curves for the LS maps indicate that the accuracy increased by almost 3% from less than 90% for LSM of AHP, to more than 93% for that of IPCM (see Figure 2). This accuracy shows the capabilities of using the IPCM approach along with the AHP method.

(a)



(b)

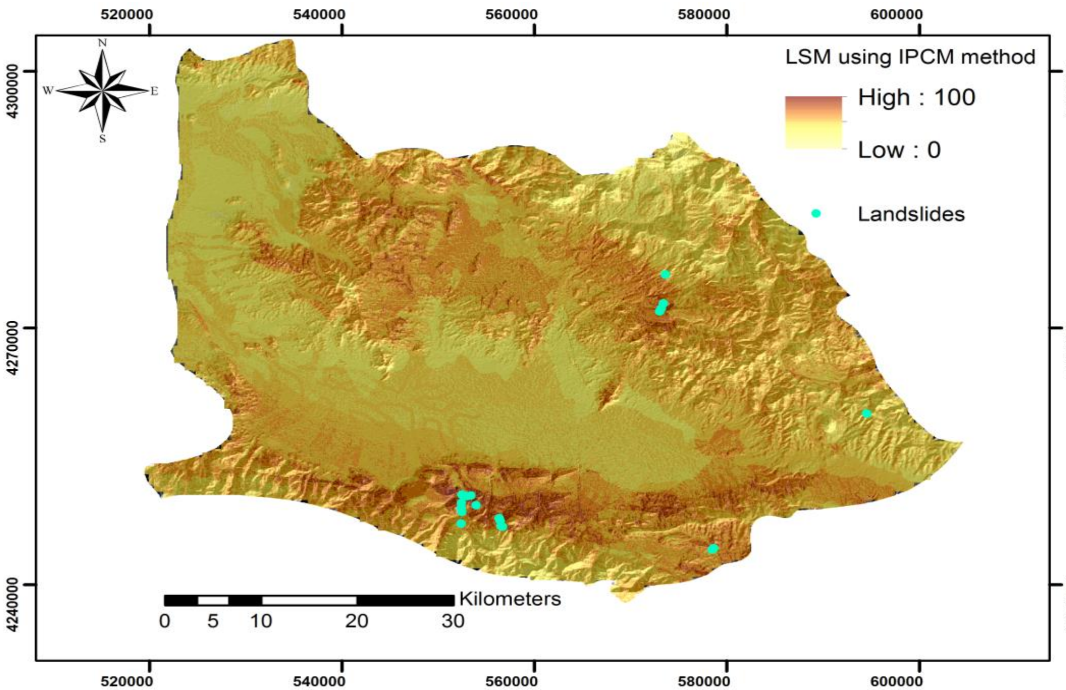


Figure 1: LSM derived from (a) AHP, and (b) IPCM

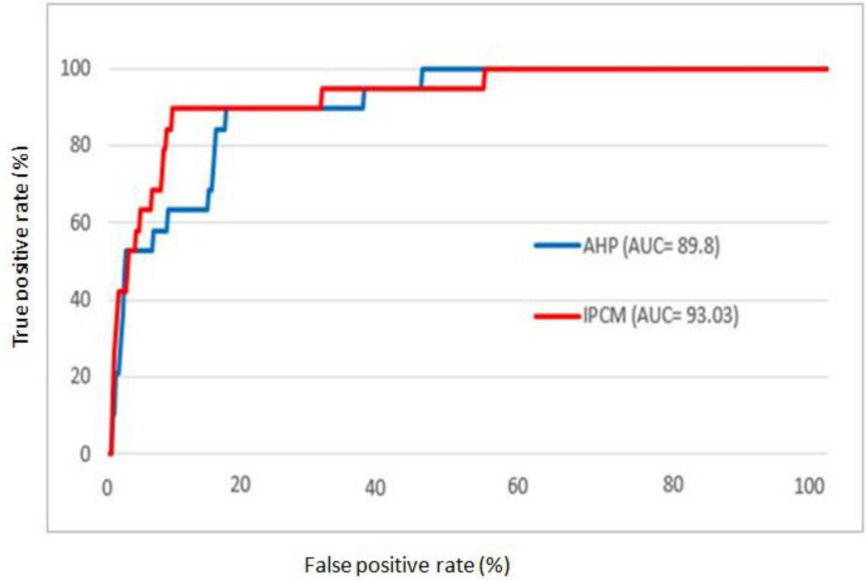


Figure 2: Prediction rate curves for landslide occurrences

3 Conclusion and future research

This research aimed to develop a novel approach for GIS-MCDA and examine its capabilities for making the AHP method more flexible and accurate. The outcome has confirmed that using IPCM helps experts to be more confident about their judgments with regard to pairwise comparison matrices. According to the results, the IPCM approach is an effective method to minimize the chance of error in AHP's pairwise decision matrix. The proposed IPCM approach can be the basis for any criteria weighing in a GIS environment and has significant importance for developing GIS-MCDA. Further research into the use of MCDA could improve our understanding of the factors and mechanisms contributing to the uncertainties in a decision-making system, and how these uncertainties affect the quality of the resulting decisions. Based on the results of the current research, future work will focus on the use of sensitivity and uncertainty analysis (i.e. global sensitivity analysis) to minimize the uncertainties in the proposed approach. We also aim to integrate fuzzy-based algorithms with the interval decision-making system proposed here and to observe the flexibility of this approach for integrating with fuzzy decision rules. The results of this research are of great importance for the geoscience community as a means of optimizing the AHP method, which is a well-known method for GIS multi-criteria decision analysis. The information provided by these landslide susceptibility maps help explain the driving factors of landslides. The results will help citizens, planners and engineers to reduce losses caused by existing and future landslide by means of prevention, mitigation and avoidance strategies, and by supporting emergency decisions.

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