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Application of the Analytic Hierarchy Process in the Multiple Criteria Decision Analysis of Retention Areas for Flood Risk Management

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Abstract

Problems of flood risk management are inherently complex, multifaceted, and involving many decision makers with conflicting priorities. Multiple criteria decision analysis (MCDA) can help to manage this complexity and decision support by combining human judgments and information in a structured decision framework. Our paper gives first a brief description of the method "Analytic Hierarchy Process" (AHP) and highlights some advantages of the AHP in the land suitability analysis and then reports about the development of a methodology by linking of Compromise Programming (CP), AHP, and GIS for the multiple criteria decision analysis of retention areas in the German part of the Elbe River flood plain. The authors describe also the development of indicators and the implementation of the methodology as an ArcGIS Extension and the AHP as a PHP web program.

Keywords: Analytic Hierarchy Process, Compromise Programming, GIS, ArcGIS Extension, PHP Web Program, Land Suitability Analysis, Retention Areas, Flood Risk Management, Elbe River.

1. Introduction

Recent natural disasters in Europe, like the floods in 2002 and 2006 or numerous landslides and earthquakes that have occurred in the course in recent years, have augmented the need for a better understanding and management of these natural phenomena. Between 1998 and 2006, Europe suffered over 100 major damaging floods, including the catastrophic flood along the Elbe and the Danube rivers in 2002 and 2006. Since 1998, floods caused at least €25 billion in insured economic losses. In addition to economic and social damage, floods may destroy the environment and reduce biodiversity. Thus flood risk management is a topic that received increasing attention in the environmental research (Schanze, 2006). Flood risk management requires decision making and therefore needs multiple criteria evaluations, e. g. multiple criteria decision analysis of retention areas. Such analysis in the context of flood risk management does not tend to be solved by conventional mathematics; rather they require logical search procedures, leading to feasible solutions of acceptable compromise. Linking of multiple criteria evaluation, mathematics such as multiple criteria optimization, and Geo Information System (GIS) can provide facilities for merging of knowledge of different disciplines such as hydrology, spatial planning, land economics, and sociology (Nijkamp et al., 1990; Poschmann et al., 1998; Malczewski, 1999; and Thinh, 2005).

Our paper presents the ongoing work of the methodological development and application of CP and AHP for multiple criteria suitability evaluation of land-use options, which was conducted at the Leibniz Institute IOER (Schanze et al., 2004; Thinh et al., 2004; Thinh & Hedel, 2004; Thinh, 2005, and Thinh &Vogel, 2006). At the current state of our work, our effort is divided in two parts: (1) to complete the software tools consisting of the ArcGIS extension for the CP and the web program for the AHP, and (2) to develop a set of indicators that help to identify locations as retention areas for flood risk management when using our methodology which combining the capabilities of CP, AHP and GIS-analysis.

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nagement of risks of extreme flood events in large river basins – the example of the Elbe River". The transnational basin of the Elbe River serves as a case study with a detailed investigation of the German part of the Elbe River flood plain (Figure 1). Scenarios of the system dynamic and mitigation alternatives are compared and ranked regarding flood risks and efforts for mitigation using new multiple criteria assessment methods.

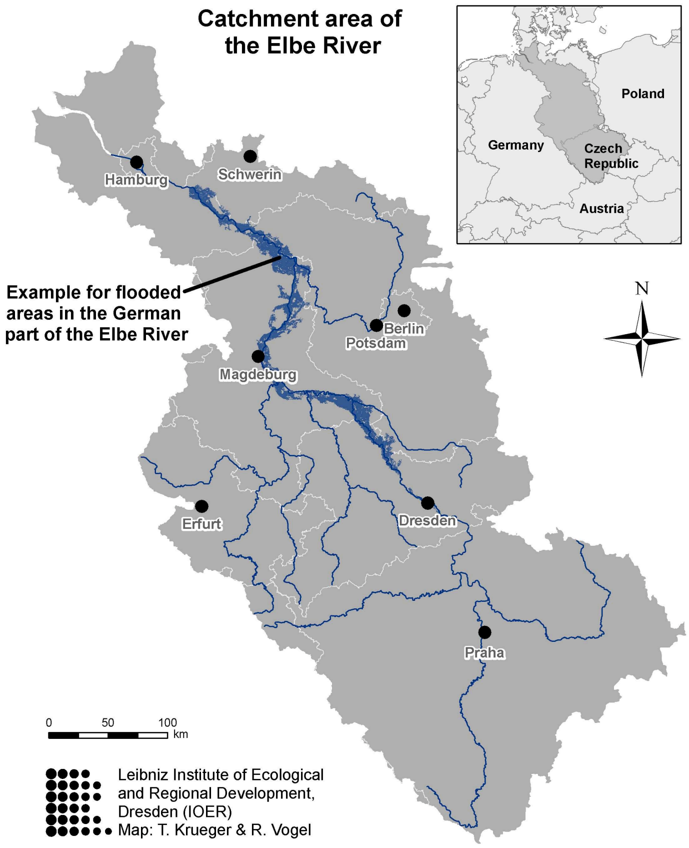

Figure 1: The VERIS-ELBE research focuses on the German part of the Elbe River

2. AHP and application in the land suitability analysis

There are now a great number of publications about MCDA and a well-established body of literature on AHP. It is well-known that the MCAD methods can be classified in multi-attribute and multi-objective decision analysis (MADA and MODA). AHP belongs to MADA methods. Despite the diversity of MCDA approaches, methods and techniques, the basic elements of MCDA are very simple: a finite or infinite set of actions (alternatives, solutions, courses of action etc.), at least two criteria, and at least one decision-maker. Given these basic elements, MCDA helps people to make decisions according to their own understanding, mainly in terms of choosing, ranking or sorting the actions. Obviously, choosing an appropriate site for an activity or facility such as retention areas for flood risk management is related to decision support and MCDA. An extensive survey of the literature on the application of AHP is beyond the scope of this paper. Therefore we focus on some main characteristics of AHP and on the application of AHP in the land suitability analysis.

At first it is useful to identify the algorithms or decision rules (or combination rules) of MCAD methods. A decision rule is a procedure that allows for selecting one or more alternatives from a set of alternatives available to the decision maker (Malczewski, 1999, p. 197). The best-known decision rules are:

1. Weighted summation,
2. AHP,
3. Ideal/reference point,
4. Outranking methods, and
5. Other (Value/Utility function approach, Concordance methods, Fuzzy aggregation operations).

The weighted summation and related methods are easy to implement within the GIS using map algebra and cartographic modelling and thus very popular. However, there is risk of the incorrect use of the method when it has been implemented without full understanding of the assumptions underlying this approach. The weighted summation methods provide a procedure where each suitability factor is assigned a score, which is multiplied by the weight of that factor. The results of the multiplications are added, and thus a site composite score is determined. This approach to site assessment is operational when standards are known. In problems, however, when no standards have been established or when intangible criteria are used to assess alternatives, the weighted summation is of limited use (Banai-Kashani, 1989, p. 685).

Table 1: Scale for Pairwise Comparison

Intensity of Importance	Definition
1	Equal importance
2	Equal to moderate importance
3	Moderate importance
4	Moderate plus
5	Strong importance
6	Strong plus
7	Very strong importance
8	Very, very strong importance
9	Extreme importance

Source: Saaty (2006).

With the AHP, T.L. Saaty founded a theory of relative measurement on absolute scales of both quantitative (tangible) and qualitative (intangible) criteria based on the judgement of knowledgeable experts and on existing measurements and statistics needed to make a decision. One main concern of the AHP is to measure intangibles. To do this, the AHP employs an underlying scale with values from 1 to 9 (Table 1), uses the comparison of pairs of alternatives/ factors/ indicators within a set of reciprocal matrices, and offers an advantage of a ratio scale, which can be effectively applied to quantify both quantitative and qualitative factors. The other concern is to treat the inconsistency in judging the relative importance of indicators. The AHP provides procedures to detect and correct this inconsistency (see Saaty, 2006, p. 356). The AHP is based on four axioms: (1) reciprocal judgment, (2) homogenous elements, (3) hierarchic or feedback dependent structure, and (4) rank order expectations. This method combines multidimensional scales of measurement into a single unidimensional scale of priorities. Consequently one can reason that also the AHP is based on the additive weighting model.

In face of the widespread use of the AHP, some criticisms have been quoted. These include the ambiguity in the meaning of the relative importance of one element of the decision hierarchy when it is compared to another element, the number of comparisons for large problems, and the rank reversal problem (Malczewski, 1999, p. 223). Rank reversal is caused by the entry of irrelevant alternatives or numerous copies of one alternative. For instance, the AHP analysis may indicate that alternative A is preferred to alternative B and B is preferred to C, possibly the introduction of multiple copies of C could lead to B being preferred to A, hence rank reversal.

Some difficulties with the weighted summation and AHP methods can be avoided by using such procedures as the ideal/reference point methods (for instance the CP method described in the next section) and the outranking methods (e. g. ELECTRE, PROMETHE, see Joerin et al., 2001).

In general, the AHP can be used in two distinctive ways. First, it can be applied to derive the relative weights associated with the considered alternatives or indicators (see the next section). Second, the AHP can be used to aggregate the priority for all level of the hierarchy structure of a MCDA problem including the level representing alternatives.

Mendoza (1997) defined land use suitability as a generic term associating a combination of factors and their impacts with respect to potential land uses. Land allocation, however, involves the process of designing an optimal mix of land uses based on their estimated suitability and perceived management objective. Land suitability analysis is a decision problem involving several factors. In general, a generic model of land suitability can be formulated as:

$$S = f(z_1, z_2, \ldots, z_n) \tag{1}$$

Where S is suitability measure; $z_1, z_2, \ldots, z_n$ are the factors/indicators affecting the suitability of the site/land. The basic problem of suitability analysis is to quantify both the individual and cumulative effects of the different indicators $z_1, z_2, \ldots, z_n$, this means that suitability analysis generally involves determining an appropriate approach to combine these indicators. For this purpose, the AHP has been often used. The advantages of the AHP for land suitability analysis are:

1. It provides a structured approach to measurement suitability by decomposing the problem into hierarchical units and levels. This allows a systematic and more in-depth analysis of the indicators which may be better understood.
2. The method relies less on the completeness of the data set, and more on expert judgements or observations about the different indicators and their perceived effects on land suitability.
3. The AHP is more transparent and thus more likely to be accepted especially when the suitability analysis will serve as a basis for land allocation.
4. The approach permits the participation of both experts and stakeholders in the analysis process.

The AHP is well presented in a significant number of publications (e. g. Saaty, 1980, 2001, 2006). Therefore, in this paper we want to describe the use of AHP for assessing the importance of weights only. This AHP algorithm has been implemented as a web program using PHP (see Section 4). For each pair of criteria, the decision maker is required to respond to a pairwise comparison question asking the relative importance of the two. Responses are gathered in verbal form and subsequently codified on a nine-point intensity scale (Table 1). After the development of the pairwise comparison matrix $A = (a_{ij})$ $(i, j = 1(1)n)$, we can compute the criterion weights as follows (see Saaty, 1980, pp. 49-51; Saaty, 2001, pp. 26-38): (1) sum the values in each column of the matrix a_{ij}; (2) divide each element in the matrix by its column total (the resulting matrix b_{ij} $(i, j = 1(1)n)$ is the normalised pairwise comparison matrix); and (3) compute the average of the elements in each row of the normalised matrix. These averages can be used as an estimate of the relative weights w_i $(i = 1(1)n)$ of the criteria being compared

$$w_i = \sum_{j=1}^{n} b_{ij} / n \quad (i = 1(1)n) \tag{2}$$

The next step is the estimation of the consistency ratio. In this step we have to investigate whether the comparisons are consistent. It involves the following operations (see Saaty 1980, 21): (1) determine the consistency vector by component-wise dividing the vector Aw (matrix A times vector w) by the vector *w*; (2) determine the average value lambda λ of the consistency vector; (3) calculate the consistency index CI.

$$\text{CI} = (\lambda - n)/(n - 1) \tag{3}$$

The quantity CI provides a measure of departure from consistency. The ratio of CI to the average random index (RI) for the same order n is called the consistency ratio (CR):

$$\text{CR} = \text{CI/RI} \tag{4}$$

(for the meaning and generating of RI see Saaty 1980, p. 21). If CR < 0.1, the ratio indicates a reasonable level of consistency in the pairwise comparison. If CR ≥ 0.1, one should reconsider and revise the values in the pairwise comparison matrix and repeat the procedure.

3. Link the capabilities of CP, AHP and GIS

For a long time researchers have been recognizing the great benefits to be gained by linking MCDA into GIS. These two distinctive areas of research can benefit from each other (Malczewski, 1999). So in a former work, Thinh (2005) suggested the link the capabilities of CP, AHP and GIS.

The basic idea of CP is to identify solutions which are closest to the ideal point as determined by some measure of distance, accepting the basic postulate that the decision maker prefers solutions as close as possible with respect to the ideal (Zeleny's axiom of choice, Zeleny, 1982). Since the ideal solution is infeasible, because of the inherent conflict of multiple objectives, it is necessary to look for compromise solutions. For that distances between each solution and the ideal point need to be calculated. To avoid a meaningless summation of values with different units and solutions biased towards those objectives that can achieve larger values, the normalization of the degrees is necessary. Thus the degree of closeness d_j between the jth objective and its ideal is given by

$$d_j = \frac{\left| z_j^* - z_j(x) \right|}{\left| z_j^* - z_{*j} \right|} \tag{5}$$

thereby x is a vector, z^*_j is the ideal value for the jth objective, and z_{*j} is the anti-ideal or nadir point for this objective. To measure the distance between each solution and the ideal point, compromise programming uses the family of L_p metrics and attempts to minimize the distance from the ideal solution (e. g. see Zeleny 1982, p. 322; Ehrgott, 2000, p. 90)

$$L_p(w) = \left[\sum_{j=1}^{n} w_j^p \left| \frac{z_j^* - z_j(x)}{z_j^* - z_{*j}} \right|^p \right]^{1/p} \rightarrow \min! \tag{6}$$

That means that any point $z(x) = (z_1(x), z_2(x), ..., z_n(x))$ is a compromise solution if it minimizes $L_p(w)$ for some choice of weights $w_i > 0$, $w_1 + w_2 + ... + w_n = 1$, and $p \geq 1$ (*p* is a natural number). $L_p(w) \rightarrow$ min has been denoted by Ehrgott 2000, p. 92, the weighted compromise programming problems. It is general practice to solve a problem for $p = 1$ (the city-block norm), $p = 2$ (the Euclidean norm), and $p = \infty$ (the maximum norm). The parameter p reflects the importance of the maximal deviation from the ideal point. For $p = 1$ all deviations are weighted equally; for $p = 2$ each deviation is weighted in proportion to its magnitude. The larger the deviation, the larger the weight is. For the case of $p = \infty$, we have a min-max-problem, that is, the compromise solution minimizes the maximum difference between the ideal point and the solution with respect to all objectives. The idea is to adapt the CP for the multiple criteria evaluation and to link CP with the AHP (for more detailed information see Thinh (2005) and Thinh & Vogel (2006). The AHP will be used to estimate the weights w_i (i=1(1)n). The methodology described here has been implemented in Arc Macro Language (AML) and in Visual Basic for Applications (VBA) as an ArcGIS extension.

4. Development of an AHP web program and an indicator set

A web-based tool was developed using the web-script language PHP (Hypertext Preprocessor) to implement the AHP especially the pairwise comparisons of indicators. On that occasion the following aspects were taken into account:

1. Simple applicability,
2. Minimisation of inputs into a necessary number,
3. Guarantee of the safety,
4. Continuous data flow,
5. Fast availability of help information.

For the guarantee of a simple applicability a clear structuring of a website is necessary (Lubkowitz, 2005, p. 259). Because of that superfluous information are renounced on the main page. Mainly it includes a dynamic created list of pairwise comparisons and a table of indicators (Figure 2). In addition two HTML fieldsets (Hypertext Markup Language) with status and consistency information like the username, the number of indicators and the number of pairwise comparisons or the consistency ratio complete the output.

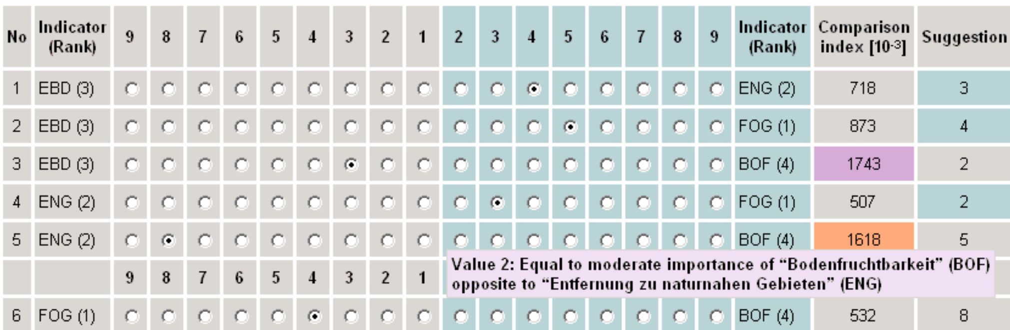

Figure 2: The web program provides hints about the importance of the scale values and names of indicators

Carefully selected experts get a username and a password which are saved in a table of a MySQL database. They shall log-in on the website and decide the priority of each combination of two objectives. Especially in the case of a large amount of comparisons it is necessary to minimise the number of user inputs.

Therefore each pairwise comparison is represented by 17 radio buttons. One mouse click is sufficient for one comparison. All comparison results will also be saved in a table of the MySQL database.

Additionally a set of PHP functions was developed to calculate matrix operations, row and column sums of matrixes, binomial coefficients, weights, and the fast recursive quick sort algorithm (Cormen et al., 2003). Based on this function set the weights of the objectives and a consistent ratio (formula (4)) will be calculated. If the value of the consistent ratio is greater than or equal to 0.1 the comparisons are inconsistent. The pairwise comparisons must be modified. To identify comparisons which contribute considerable to the inconsistency, a method was developed to calculate average consistency ratios for each objective and for each pairwise comparison. High index values indicate pairwise comparisons which do only fit in a less manner to the whole comparison set. The experts have to adjust their pairwise comparisons, usually such with the highest index values, until the consistency ratio of the whole comparison set is lower than 0.1.

Afterwards the calculated weights were saved to a corresponding table in the MySQL database. The average value for the weights of objectives of all experts will be used as input in the ArcGIS Extension "Compromise Programming".

The aim of our work is to identify the suitability of areas in the floodplain of the Elbe River. This involves areas in the five German federal states Saxony, Brandenburg, Saxony-Anhalt, Mecklenburg-Western Pom-erania and Lower Saxony for retention purposes. Retention means the temporary storing of water (cf. Patt et al., 1998, p. 127) into the water cycle. Retention means the withhold on surfaces of plants, in the soil and groundwater body as well as into the stream network and in river floodplains. For our purposes we limit the term retention to areas in and near floodplains.
To do this we distinguish four retention types:

1. Relocation of dikes,
2. Uncontrolled flood polder,
3. Flood channel, and
4. Controlled flood polder.

These are different in their naturalness and in both the number and dimension of necessary buildings. A set of indicators is categorized according the effectiveness (soil, water, flora/ fauna, people, culture/ goods, landscape) and usability (inhabitation, business and industry, traffic, supply/ disposal, regeneration/ spare time). Furthermore nature reserve areas and hydrological properties of the areas will be considered. The set of indicators will be used to describe the function suitability and the impact potential. Using the CP algorithm the spatial resistance can be calculated for all areas. Combined with the hydrological suitability the retention suitability of the areas can be determined. The hydrological suitability for instance depends on the depth of flooding for a defined flood event (HQ100), the hydrological neighbourhood characteristics or the slope. The development of an indicator set is still in treatment and therefore our work can not be completed yet.

The developed AHP web program allows a professional application of AHP to estimate the relative weights for a given set of indicators or criteria. The participation of decision makers and/or experts is guaranteed. AHP and the provided tools support not only the comparison process in an effective way. They also help to shorten this process. It delivers, for example, information relevant for the question, where can the causes lie for inconsistency.

Bibliography

Banai-Kashani, R. (1989): A new method for site suitability analysis: The Analytic Hierarchy Process. Environmental Management, Vol. 13, No. 6, 685-693.

Cormen, T., Leiserson, C., Rivest, R., Stein, C. (2003): Introduction to Algorithms, MIT Press, Cambridge.

Ehrgott, M. (2000): Multicriteria Optimization. Lecture Notes in Economic and Mathematical Systems 491, Springer-Verlag Berlin.

Joerin, F., Theriault, M., Musy, A. (2001): Using GIS and outranking multicriteria analysis for land-use suitability assessment. Int. J. Geographical Information Science, 15, 2: 153-174.

Lubkowitz, M. (2005): Webseiten programmieren und gestalten. 2., erweiterte Auflage, 3. Nachdruck. Bonn: Galileo Press.

Malczewski, J. (1999): GIS and multicriteria decision analysis. John Wiley, New York.

Mendoza, G. (1997): A gis-based multicriteria approach to land suitability assessment and allocation. In: Seventh Symposium on System Analysis in Forest Resources, Traverse City.

Nijkamp, P.; Rietveld, P.; Voogd, H. (1990): Multicriteria evaluation in physical planning. Amsterdam.

Patt, H.; Jürging, P.; Kraus, W. (1998): Naturnaher Wasserbau: Entwicklung und Gestaltung von Fließgewässern. Springer-Verlag, Berlin, Heidelberg, New York.

Poschmann, C.; Riebenstahl, C.; Schmidt-Kallert, E. (1998): Umweltplanung und -bewertung. Justus Perthes Verlag, Gotha.

Saaty, T.L. (1980): The Analytic Hierarchy Process. McGraw-Hill, New York.

Saaty, T.L. (2001): Decision Making With Dependence And Feedback – The Analytic Network Process. RWS Publications Pittsburgh.

Saaty, T.L. (2006): The analytic hierarchy and analytic network processes for the measurement of intangble criteria and for decision-making. In: J. Figueira; S. Greco; M. Ehrgott (Eds.): Multiple Criteria Decision Analysis State of the Art Surveys. Springer New York.

Schanze, J. (2006): Flood Risk Management - A Basic Framework. In: Schanze, J.; Zeman, E.; Marsalek, J.: Flood Risk Management - Hazards, Vulnerability and Mitigation Measures. Springer, Berlin, 1-20.

Schanze, J., Thinh, N.X., Walz, U., Ferencsik, I., Göncz, A. (2004): Suitability of compromise Programming as a land use optimisation approach considering ecological aspects. Final Report, IOER Dresden & VATI Budapest.

Thinh, N.X., Hedel, R. (2004): A Fuzzy Compromise Programming Environment for the Ecological Evaluation of Land Use Options. Proceedings of the 18th International Conference Informatics for Environmental Protection, CERN Geneva, Vol. I, Editions du Tricorne, pp. 614-623.

Thinh, N.X., Walz, U., Schanze, J., Ferencsik, I., Göncz, A. (2004): GIS-based Multiple Criteria Decision Analysis and Optimization for Land Suitability Evaluation. In: Wittmann, J.; Wieland, R. (Hrsg.): Simulation in Umwelt- und Geowissenschaften. Workshop Müncheberg. Shaker Verlag Aachen, pp. 161-181

Thinh, N.X. (2005): Entwicklung von mathematisch-geoinformatischen Methoden und Modellen zur Analyse, Bewertung, Simulation und Entscheidungsunterstützung in Städtebau und Stadtökologie. Accepted Habilitation Thesis, 182 pages, Faculty of Agricultural and Environmental Sciences, University Rostock (in German).

Thinh, N.X.; Vogel, R. (2006): GIS-based multiple criteria analysis for land-use suitability assessment in the context of flood risk management. In: Kremers, H., Tikunov, V. (Eds.): InterCarto-InterGIS 12. International Conference on Geoinformation for Sustainable Development, Berlin, Deutsche Gesellschaft für Kartographie, pp 1-12.

Zeleny, M. (1982): Multiple Criteria Decision Making. McGraw-Hill, New York