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A GIS application to enhance cell-based information modeling

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Abstract

Maps have been major sources of information for a long time. Geographic Information Systems (GIS) use digital data, elevation models, satellite images, expert systems and related open source information for planning, detection, evaluation and decision making. Maps as well as GIS use spatial attributes of data in particular. Spatial Information derived is a feature of both data and language to communicate results of analysis and interpretation.

A natural language approach to geographic concepts is discussed focusing on the cognitive aspects of categorizing spatial terms, which are represented by vague descriptions. Scientific analysis, however, requires a formal representation of spatial terms. The translation of linguistic concepts to spatial terms like “steep slopes” involves inherent uncertainties that are dealt with by implementing fuzzy logic tools to computer-based GIS. MapModels is a programming language based on ArcView[®] GIS that allows users easily to comprehend geographical (spatial) terms by means of analytical tools including membership models. A flowchart interface is preferred to a line-code oriented programming language thus enabling the user to focus on a particular problem rather than a complex programming exercise. Examples are given on how MapModels utilizes the vagueness of geographic description in GIS analysis. This paper shows, how MapModels enhances the powerful options of GIS-based spatial analysis in obtaining information from cell-based images. © 2002 Elsevier Science Inc. All rights reserved.

Keywords: Fuzzy sets; GIS; Spatial analysis; Semantic modeling; Graphical programming languages

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1. Introduction

Geographically referenced data are considered essential parts of Geographic Information Systems (GIS), which represent our knowledge of the real world. For a long time maps have been the major tool to represent the world and have been used as main non-digital source of information about earth. GIS, however, use digital data layers, elevation models, satellite images, expert systems and related open source information for planning, detection, evaluation and decision making. GIS combine the potentials of both large databases and maps. Maps as well as GIS use spatial attributes of data. The spatial information resulting from both technologies can be described as a feature of both the data used and their linguistic expressions to communicate results of analysis and interpretation [1].

Language is a major part of communicating knowledge in a decision making process. Natural language has optimized the way of deriving information and making decisions based on common-ground experiences [9]. To make it computable one has to formalize it and use stricter language representation applying crisp rather than vague and undetermined categories. Mapping data and facts in terms of a formal language is a complex task due to context dependency and inherent uncertainty. This situation may lead to a strategy to avoid problems: *to say that all [natural] language is vague is a favorite method for evading the problems involved* [2].

Due to the fact that natural language representation of geographic facts is a process of translation from real space to perceptual space to linguistic space [3] the cognitive processes may not be neglected. Humans simplify reality, based on their experiential use of a particular category, e.g. ‘steep slope’, thus grasping the information behind a complex phenomenon.

In addition, the actual verbal expression adds uncertainty to geographical facts. This leads to results carrying the following ideas:

- Spatial metaphors have an important function in our everyday language (e.g. the price is *way out* of our possibilities). Linguistic expressions carry spatial components without having a spatial reference [4].
- Almost all grammatical classes have a spatial component (*far, the next, through*) [5].
- The majority of descriptions is qualitative.

Man is capable of making decisions based on vague and uncertain concepts because of his ability to grasp the information that is stored away in a linguistic expression. The direct translation of such processes to formal languages is not an easy task. This paper shows how GIS technology may contribute to a better understanding of formal definitions of geographic categories.

2. Methods and tools

GIS use the concept of layers to represent real world data on a spatial basis. GIS use spatial attributes of data, namely x and y coordinates, to represent geographic data. Many techniques exist to model spatial concepts like ‘neighborhood’ or ‘contiguity’. Other concepts are largely ignored because of a lack of adequate modeling tools. The introduction of Fuzzy Logic to GIS Software enables the user to model aspects of vagueness and ambiguity in linguistic categories. A logical concept to formalize spatial knowledge with a fuzzy logic-based mathematical model has to map language characteristics without losses. To use inherent uncertainty is therefore a crucial task in trying to overcome the problem of *mathematics is either uncertain or inapplicable*, as Albert Einstein is quoted in [2].

MapModels has been developed by Riedl [7,8]. The interface is based on ArcView[®], a major GIS Desktop system. MapModels provides means to use fuzzy logic to evaluate information that is spatially referenced like ‘steep slopes’ and ‘southern aspect’. MapModels has been developed because there is a general lack of user friendly interfaces to spatial analysis software. The main

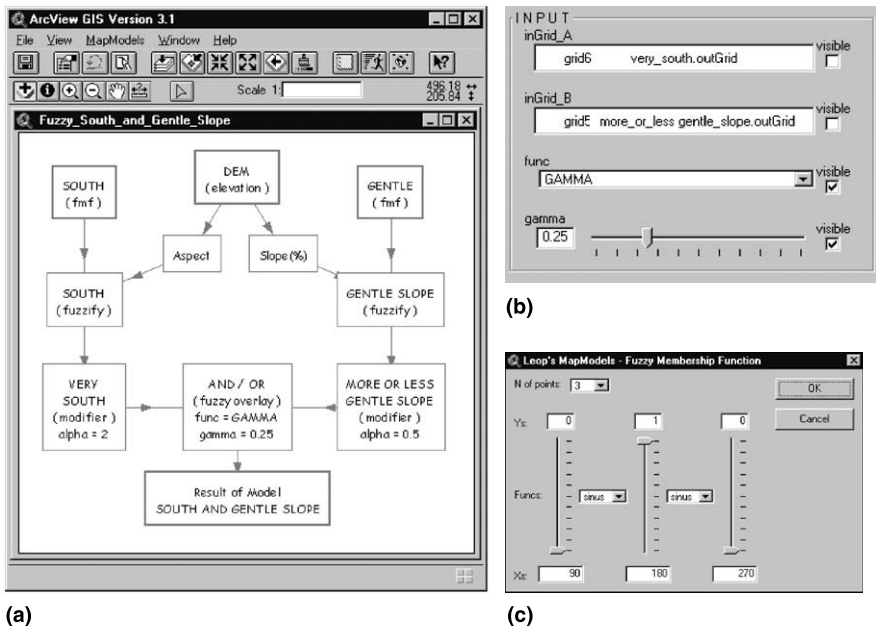


Fig. 1. Deriving fuzzy geographical categories from a Digital Elevation Model (DEM). (a) MapModels: Data Flow and User-interface. (b) Dialogue Fuzzy-Overlay (parts). (c) Dialogue Mask – ‘southern slopes’.

interface of this application is a flowchart-based programming language that allows the user to virtually drag and drop fuzzy (and other spatial) analytical parameters, maps and combinations thereof. A flowchart-based user interface enables even a newcomer to programming languages to use fuzzy technology in GIS. Fig. 1(a) shows the user interface, Fig. 1(b) the dialogue window for map overlay and Fig. 1(c) the simulation interface for determining membership functions.

3. Application

GIS are often used to provide maps for decision making processes. One example: someone is about to retire and is looking for a suitable place to build a house. He has clear ideas where he wants to build it: it has to be an area that is southerly exposed and that lies on a gentle slope. All of these geographical categories are easily comprehended by humans but it is very difficult to tell a GIS to find a *suitable* place. The colloquial ‘southern’ lies somewhere between east and west, ‘gentle’ is not very well defined either. Both are vague aspects of information and can be derived from a digital elevation model expressed as degrees or percent, respectively. In addition, modifiers, also known as hedges, can be used to modify the concept of a ‘southern’ area. The advantage of doing

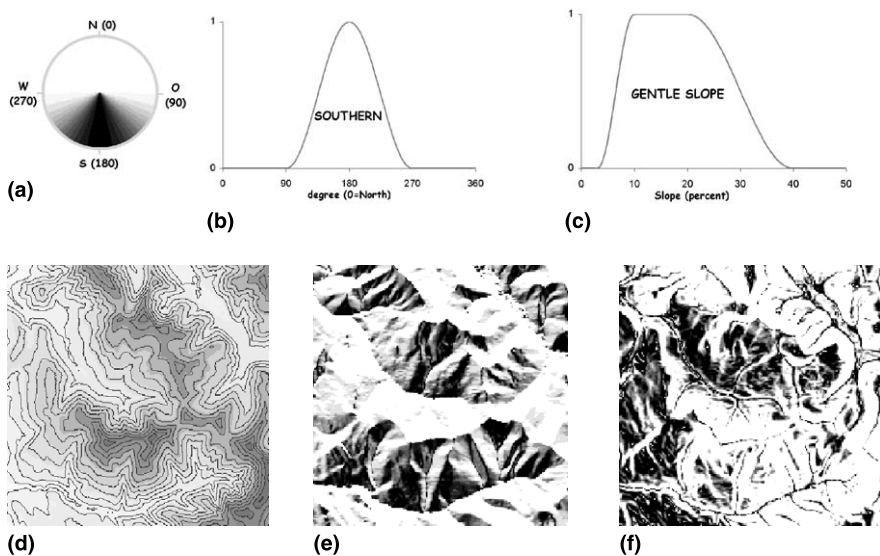


Fig. 2. Modeling linguistic expressions in a GIS using fuzzy membership functions (FMF): (a) southern fuzzy model; (b) FMF southern; (c) FMF gentle slope; (d) DEM; (e) fuzzy southern aspect; (f) fuzzy gentle slope.

this by using a GIS clearly lies in the immediate visualization of fuzzy concepts in terms of real world representations or maps. Figs. 2(a)–(c) show the term ‘southern’ modeled with MapModels using a bell shaped curve with degrees of membership lying between 90° and 270° based on the assumption that the perfect degree representing the concept of southern is 180° . A gentle slope is defined as somewhere between 3% and 40% with a core area of 10–20%. The immediate implication to map modeling can be seen in Figs. 2(d)–(f). The darker the image the more a linguistic concept (southern) is represented by geographical data.

Developing a fuzzy GIS application involves three tasks that are believed to be of crucial importance:

- The selection of an appropriate membership function.
- The selection of a suitable operator to combine fuzzy sets.
- The definition of linguistic hedges to further describe fuzzy sets.

For none of them evaluation methods exist in terms of geographical coherence.

3.1. Hedges (linguistic modifiers)

‘South’ is not always exactly ‘south’, it may become ‘more or less south’ in the course of the decision making process. The same is true for any other geographical category. As humans we use linguistic modifiers (hedges) to describe those particular situations. Although questioned by linguists, three formal concepts are provided by fuzzy logic to be added to a fuzzy modeling process:

- powered hedges for concentration and dilation “southern” $\Rightarrow$ “more or less southern”: $\mu_{\text{very}}(x) = \mu^2(x)$; $\mu_{\text{more or less}}(x) = \mu^{1/2}(x)$,
- shifted hedges map changes in meaning “steep slope” $\Rightarrow$ “very steep slope”: $\mu_{\text{very}}(x) = \mu(x + s)$,
- scaled or generic hedges combine both of the above but are not used very much. Fig. 3 shows the results after applying hedges.

Please note, that the concept of “very” is modeled by a powered hedge in the case of “very southern” as shown in Fig. 3(a). This causes a change of the membership but has no impact on the core representation of data representing “southern”. The concept of “very” in the case of “very steep slope” in Fig. 3(b), however, causes a change in the support of a fuzzy set by shifting the membership to the right.

3.2. Map overlay

A main task in GIS is deriving information from different maps using a map overlay. Maps are combined by algebraic means. For fuzzy maps operators are needed. An important aspect in combining information is compensation. The

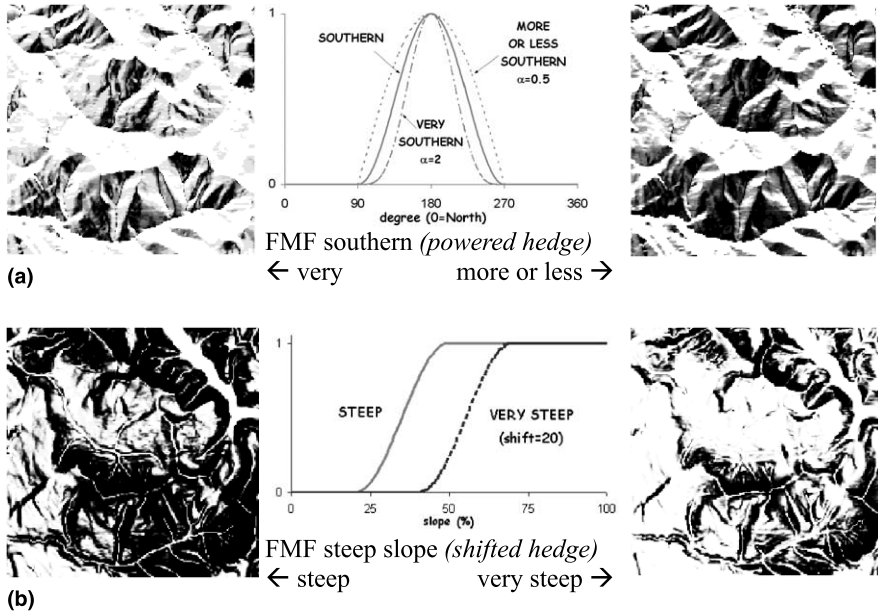


Fig. 3. (a) Fuzzy Modifier very and more or less for linguistic expression "southern". (b) Fuzzy Modifier very for linguistic expression "steep".

concept of compensation is used to decrease or increase the influence of one (possible) information concept over another by adjusting operators. It is therefore crucial to make these operations comprehensible, because fuzzy logic has the advantage of providing not only one but many results to represent the vagueness of concepts and their combinations. Unfortunately there is no operator that adequately models human compensation. Classical operators tend towards extreme positions. The operators chosen for this work therefore rely on gamma operators [10]. To develop an appropriate setting of parameter γ is crucial to receiving meaningful results in terms of modeling human decision processes. Two examples out of many are:

$$\mu_{\text{comp}}(\mu_A, \mu_B) := (\mu_A \cdot \mu_B)^{1-\gamma} \cdot (1 - (1 - \mu_A) \cdot (1 - \mu_B))^\gamma, \quad \gamma \in [0, 1], \quad (1)$$

$$\mu_{\text{MinMax}}(\mu_A, \mu_B) := \gamma \cdot \min(\mu_A, \mu_B) + (1 - \gamma) \cdot \max(\mu_A, \mu_B), \quad \gamma \in [0, 1]. \quad (2)$$

Priorities also have to be considered. What is more important to me gets a bigger weight (e.g. 'mainly south'). This is realized with

$$\mu_{\text{Weight}}(\mu_A, \mu_B) := (1 - \gamma) \cdot \mu_A + \gamma \cdot \mu_B, \quad \gamma \in [0, 1]. \quad (3)$$

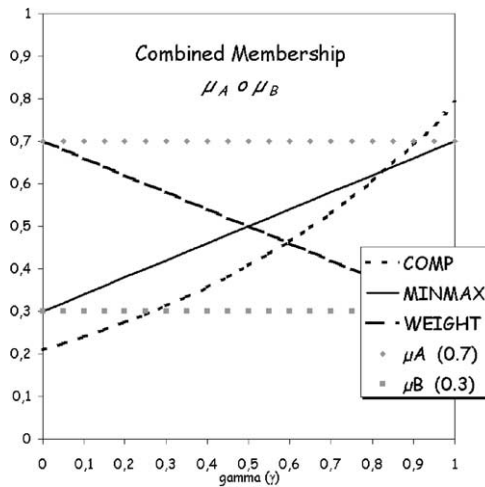


Fig. 4. The effect of different operators on the GIS result.

Fig. 4 shows the effect of using different parameters γ on the result of operations on fuzzy membership degrees. Several other examples are given in [6]. Fig. 5 shows the results of the effect of an increasing value of parameter γ on the results of the combinations using compensating operators (comp and min/max) compared to a priority-based weight operator. The operators are applied to a data set of a mountainous region in Austria. Following the linguistic interpretation as described in previous chapters results in a multidimensional interpretation space. The first two images in the first row in Fig. 5 show the desired areas in black, where slopes are “gentle AND southern” using a compensating operator defined in (1) as well as a min/max operator defined in (2). Both kind of operators seek to compensate the knowledge of the input image to a certain degree, that is determined through the value of γ . From $\gamma = 0$ (AND) to $\gamma = 1$ (OR) some possible combinations of “southern aspects and gentle slopes” are shown. Clearly you can see, that a low value of γ leads to a more crisp result whereas a high value of γ tends to somewhat exaggerate compensation in the resulting image. The third image of the first row has been obtained using a priority-based weight operator as defined in (3). Next to that image it is indicated that “southern” has been given a priority to the decision-making process with $\gamma = 0$. For $\gamma = 1$ the result shows “gentle” to be more important. It is remarkable, though, that $\gamma = 0.5$ has the same effect on the result using compensating as well as priority-based weight operators. Obviously similar interpretations are supported while using a different concept of compensation. This opens the ground for discussions on the meaning of operators in GIS with interpretations ranging from ‘AS WELL AS’ over ‘RATHER THIS ONE THAN ANOTHER’ to ‘DOESN’T MATTER, JUST USE ANYONE’.

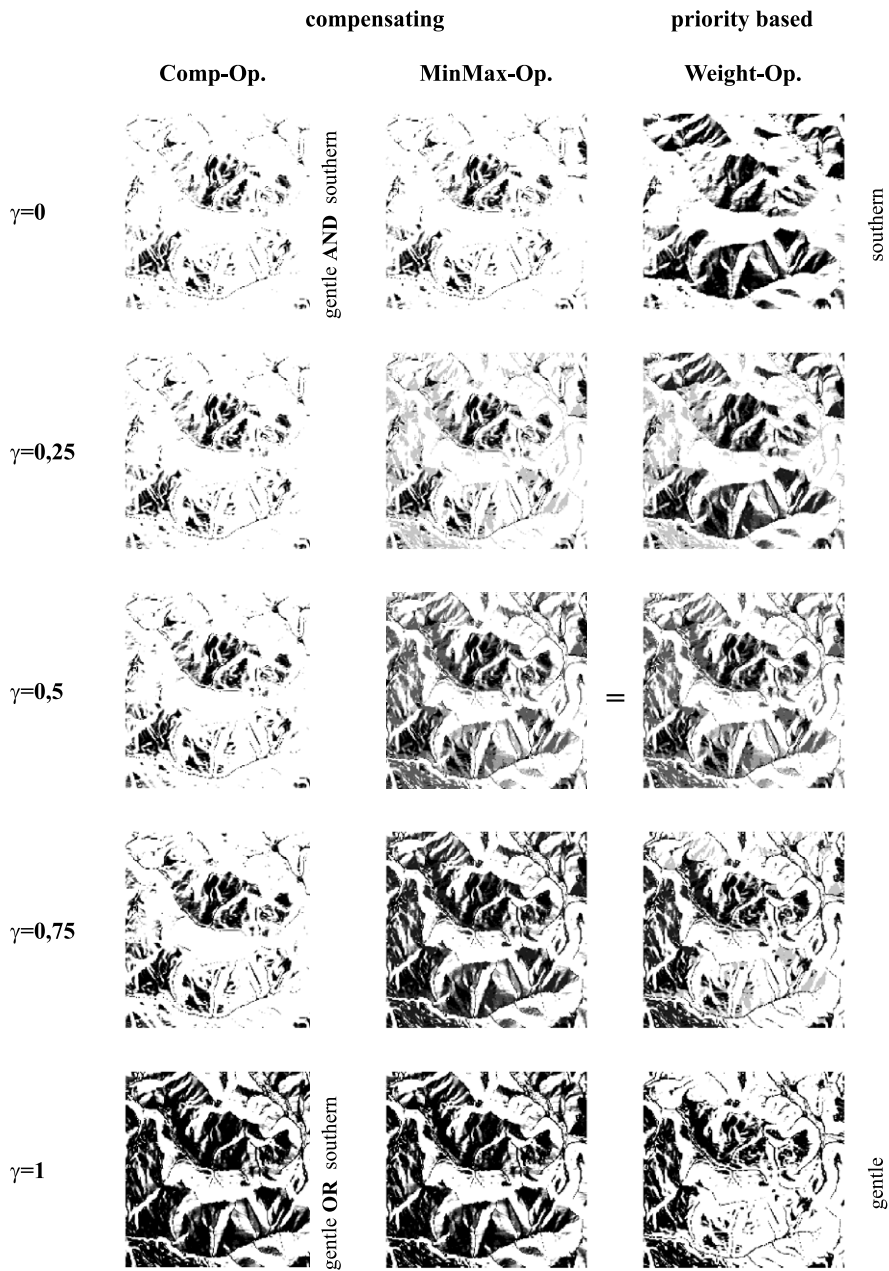


Fig. 5. Possible interpretation space of combining “southern aspects and/or gentle slopes”.

4. Discussion

The paper discussed an interface that uses fuzzy technology for Geographic Information Systems. It discussed the concepts of deriving information from maps and of overlay being an important task in GIS analysis. The following points turn out to be important for fuzzy logic applications in GIS:

- The relationship between linguistic and logic operators has to be defined especially working with geographic applications.
- The actual meaning of slope, for example, has to be discussed before using fuzzy logic. It cannot be determined from fuzzy maps.
- Linguistic studies have to be followed more closely so that ‘common world’ parameters can be defined in the design of human–computer interfaces.

Possible applications of fuzzy GIS include

- information desks to answer questions on near barber shops, relatively cheap flats and so on,
- socioeconomic data modeling with a semantic perspective,
- safeguards when using maps as information tools.

We are used to ‘understand’ maps better than plain data files. Whenever data and information have a spatial context the combination of GIS and Fuzzy Logic provides a powerful and flexible tool in communicating knowledge.

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