FUZZY LOGIC ANALYSIS FOR MODELLING OF NATURAL RESOURCE PROCESSES

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ABSTRACT

Models applied with Geographic Information Systems (GIS) in relation to Natural Resources processes often deal with uncertainty factors. These factors can be of different magnitudes. Fuzziness is a type of imprecision characterising classes that for various reasons cannot have or do not have sharply defined boundaries. Fuzzy logic analysis is based on expert knowledge and experience. There are several fuzzy set operators usually used in models related to Natural Resource Management. These are the operators OR, AND, Fuzzy algebraic product, Fuzzy algebraic sum, Fuzzy combination of sum and product and the Fuzzy operator factor gamma. To apply a fuzzy knowledge based exploratory model requires the following steps: determination of the model structure, formulation of fuzzy knowledge base, selection of fuzzy knowledge processing methods, calibration and validation. The membership functions can be seen as the "knowledge base" and the inference network and fuzzy combination rules as the inference engine. Fuzzy logic is an important tool in expert systems where uncertainty of evidence is important. .Fuzzy logic analysis is based on expert knowledge and experience.

An example is given of a land degradation model in the Murmuntani catchment, located in the Chapare province (department Cochabamba, Bolivia). Different fuzzy operators were applied to combine thematic information on geology, geomorphology, land cover, land use, erosion and slopes. It is shown in the model that fuzzy sets can be very useful when dealing with uncertainty, vagueness and complexity of data.

1 INTRODUCTION

This paper shows how fuzzy logic can be applied in natural resource modelling. In the first part a general explication is given on the concept of fuzzy logic concepts and operators. The second part deals with a land degradation model of a catchment in the Andes Cordillera (mountain range) near Cochabamba, Bolivia. It demonstrates the application of different fuzzy sets to estimate the risk of land degradation. The model was applied in ILWIS2.23. The general idea about the model is to use fuzzy sets when we deal with uncertainty, vagueness and complexity of data. Actually this is quite often the case with modelling of natural resource data. In many cases data are treated as if they are precise to facilitate (empirical) data analysis. Fuzzy set logic is a very useful additional tool in geographic information systems but it is a subjective way of modelling and therefor it is very important that the final products are well calibrated and validated.

2 FUZZY LOGIC IN GENERAL

Models applied with GIS in relation to Natural Resources processes often deal with uncertainty factors. These factors can be of different magnitudes for example when certain properties are difficult to measure (like some soil properties such as strength of soil structure), if data are insufficient for statistical analysis or even when relations between indicators are not clearly known. In these cases an approximation or evaluation can only be made based on expert experience. Fuzzy logic analysis is based on expert knowledge and experience. Fuzziness is a type of imprecision characterising classes that for various reasons cannot have, or do not have, sharply defined boundaries. These inexactly defined boundaries are called fuzzy sets (Burrough, 1998). The models are empirical and can be applied to natural resource data when imprecise data have to be analysed or when vague knowledge has to be represented and processed in the form of linguistic rules with imprecise terms. Fuzziness is an admission of possibility that an individual is a member of a set. The assessment of the possibility can be based on subjective, intuitive expert-knowledge.

Many classification models in Natural Resources are based on binary membership functions. This means that an individual is a member, or is not a member, of any given set (True or False). But in many cases in Natural Resources such a division is much too ad-hoc. Fuzzy sets, however, admit the possibility of partial membership especially when class boundaries are not sharply defined.

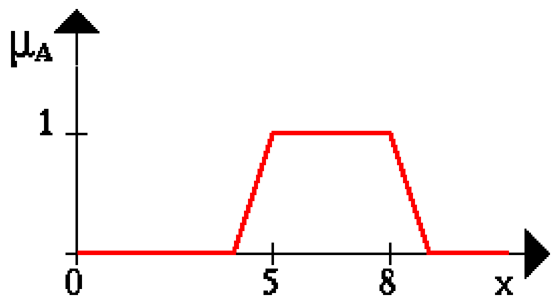
To apply a fuzzy knowledge based exploratory model requires the following steps: determination of the model structure, formulation of fuzzy knowledge base, selection of fuzzy knowledge processing methods, calibration and validation. To broaden the practical application concept of fuzzy logic, an analysis was carried out.

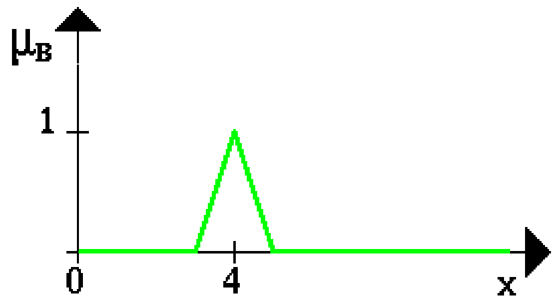
3 THE FUZZY SET MODELS

In crisp set theory there exist two possibilities, either a parameter belongs to the set and is classified as 1 or the parameter does not belong to the set and is classified as 0. This concept is rigid and does not accept any ambiguity. In contrast fuzzy sets do accept vagueness or uncertainty. In fuzzy set theory a range of values can be applied between 0 and 1 eliminating sharp boundaries. If 1 is assigned to an individual it means that the individual belongs to the fuzzy set to a greater degree than when a lower value is assigned. These ranked values between 0 and 1 are known as "membership grades" or "certainty factors" (degrees of belief). Very often a GIS model will consist of linguistic variables as "low", "moderate" and "high". These variables can also be defined by fuzzy sets. In total there are six operators/models related to fuzzy set analysis: These are the operators OR, AND, Fuzzy algebraic product, Fuzzy algebraic sum, Fuzzy combination of sum and product and the Fuzzy operator factor gamma.

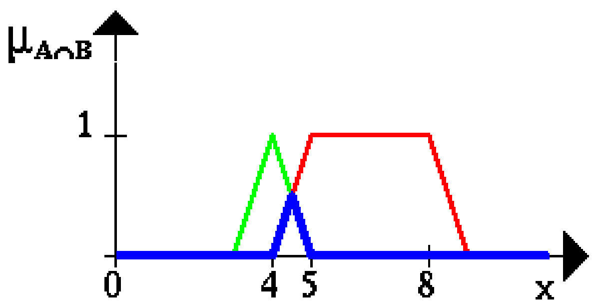
3.1 Fuzzy AND

In order to clarify this operator , the following example is given. Let *A* be a fuzzy interval *between* 5 *and* 8 and *B* be a fuzzy number *about* 4. The corresponding figures are shown below.





The following figure shows the fuzzy set *between* 5 *and* 8 **AND** *about* 4 (notice the blue line).

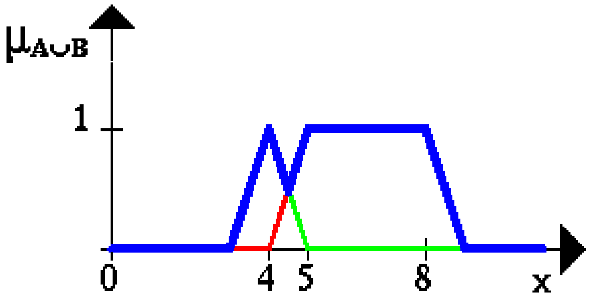


(source of example: Bauer, Nouak and Winkler, 1996)

In general the fuzzy AND statement will result in membership values controlled by the minimum values of the input maps.

3.2 Fuzzy OR

In relation to the example given at “Fuzzy AND”, the fuzzy set *between* 5 *and* 8 **OR** *about* 4 is shown in the next figure (again, it is the blue line).



(source of example: Bauer, Nouak and Winkler, 1996)

The result of the fuzzy OR statement will result in membership values controlled by the maximum values of the input maps. Typical applications of the Fuzzy AND and Fuzzy OR operators are overlay functions in Geographic Information Systems.

3.3 Fuzzy algebraic product (minimization):

$$\mu c = \prod_{i=1}^{n} \mu(x)$$

In other words: μc is the product of different maps x (i=1, 2, ...n) with fuzzy membership-values in the range (0 to 1).

The results of this product tend to be very small, due to the effect of multiplying several numbers with values less than 1 (example: 0.8 * 0.4 =0.32). The output is always smaller than, or equal to, the smallest contributing membership value, and is therefore decreasive.

3.4 Fuzzy algebraic sum (maximization):

$$\mu c = 1 - \prod_{i=1}^{n} (1 - \mu(x))$$

In the case of applying the fuzzy algebraic sum the result is always equal to, or larger than, the largest contributing fuzzy membership value, and is therefore increasive. Two pieces of evidence that both favour a hypothesis reinforce one another and the combined evidence is more supportive than either piece of evidence taken individually. For example, the fuzzy algebraic sum of (0.75, 0.5) is 1-(1-0.75)*(1-0.5), which equals 0.875. The increasive effect of combining several favourable pieces of evidence is automatically limited by the maximum value of 1.0, which can never be exceeded. (Bonham-Carter, 1994)

3.5 Combination of fuzzy sum and product:

$$\mu c = W_1 * \mu(x_1) + W_2 * \mu(x_2) + \ldots W_n * \mu(x_n) \text{ where } \sum_{i=1}^{n} W = 1$$

With the fuzzy algebraic product and fuzzy algebraic sum we respectively minimize and maximize the results. To avoid these extreme values it is possible to apply the method of combination of fuzzy sum and product. In this case μc is the sum of different maps x (x=1, 2, ...n) with fuzzy membership-values in the range (0 to 1) multiplied by a weight factor (W), the sum of these factors (W_1+W_2+... +W_n) should be equal to 1 (Valenzuela, 1994).

3.6 Fuzzy factor gamma:

$$\mu c = (\prod_{i=1}^{n} \mu(x))^{\gamma} \; * \; (1-\prod_{i=1}^{n} (1-\mu(x))^{1-\gamma}) \qquad \text{where } 0 < \gamma < 1$$

The fuzzy factor gamma model is another combination of the fuzzy algebraic product and fuzzy algebraic sum. The gamma factor (γ) is a parameter in the range (0,1). When the gamma factor is defined as 1 the result will be equal to the fuzzy algebraic sum. When the gamma factor is defined as 0 the result will be equal to the fuzzy algebraic product. Judicious choice of γ produces output values that ensure a flexible compromise between “increasive” tendencies of fuzzy algebraic sum and the “decreasive” effects of the fuzzy algebraic product (Bonham-Carter, 1994).

Which method should be selected depends on the type of application and the complexity of the problem. In practice it may be desirable to use a variety of different fuzzy operators. In this case first the intermediate hypothesis should be met by applying a fuzzy set operator on different maps. The resulting map can be combined again with other reclassified maps (with fuzzy set membership values) using another type of fuzzy set operator. This final outcome is a fuzzy membership map for the proposition of the final hypothesis. Such a series of steps can be defined in a “inference network”(fig.1).

4 THE LAND DEGRADATION MODEL

The Murmuntani catchment is located in the Chapare province (department Cochabamba, Bolivia), near the village Tiraque at an altitude of 3996 - 4602 meters above sea level. The catchment is part of the "Cordillera Oriental", consisting of a mountainous landscape with very steep slopes (Fig.2). The area of the catchment is calculated to be about 6.57 km^2.

The objective of the model is to estimate the land degradation risk. The methodology chosen was the fuzzy logic method because these areas deal with a minimum availability of data, uncertainty factors in relation to the classifications, and have a low accessibility.for fieldwork verification. First an interpretation was carried out using a Landsat5 image, aerial photographs and topographic maps on geology, geomorphology, land cover, land use, and erosion. The results were verified during fieldwork and corrected. To create a Digital Elevation Model (DEM) of the catchment, the contour lines were digitised in ILWIS2.23 and interpolated. From the DEM a slope map was generated.

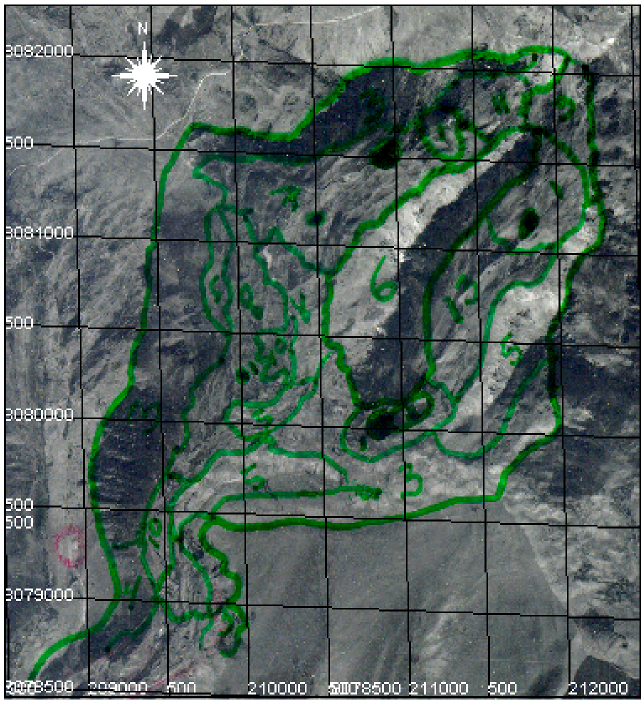


Fig. 2. Aerial Photograph of the Murmuntani Catchment

Each thematic map was reclassified in a risk map, containing the membership grades. For this purpose, the significant factors were determined. In this paper the creation of the erosion risk map is demonstrated to clarify the first step. In the same way the geology, geomorphology land cover and land use risk maps were calculated. The significant factors concerning erosion (in this study area) were defined by the stability of the soil, support rate to sedimentation, predominant slope, soil degradation rate and protection rate (land cover). A table (table 1.) was generated in which for each map unit a membership value (between 0 and 1) was assigned concerning each significant factor (element)

If 1 is assigned to an individual (map unit) it means that the individual belongs to the fuzzy set (erosion risk) to a greater degree than when a lower value is assigned. To assign the final membership grade representing the sub-membership grades, the most adequate Fuzzy set operator had to be selected. In the case of erosion the worst scenario was chosen, to never underestimate the erosion risk.

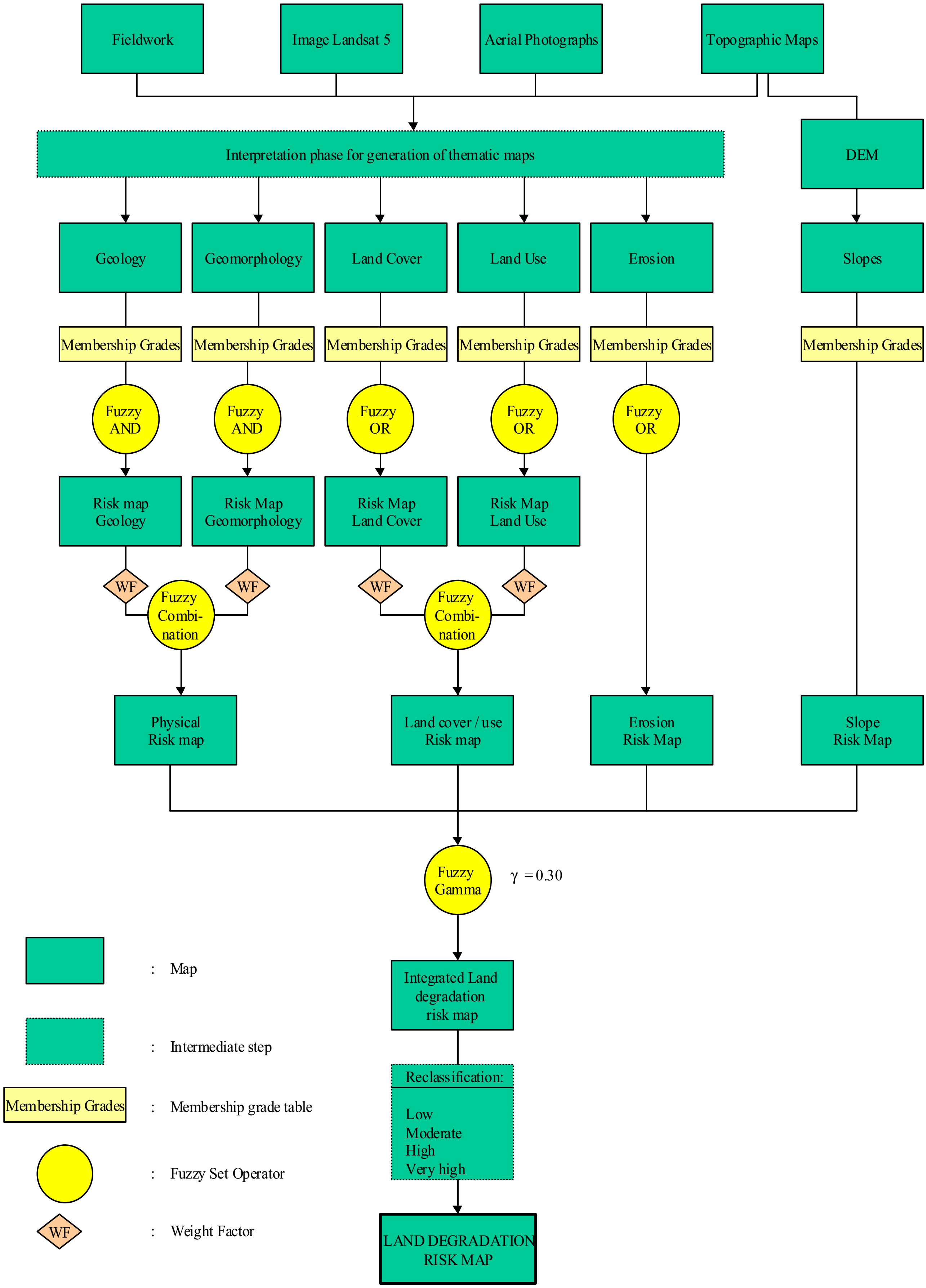


Fig. 1. Inference Network of the Land Degradation Model

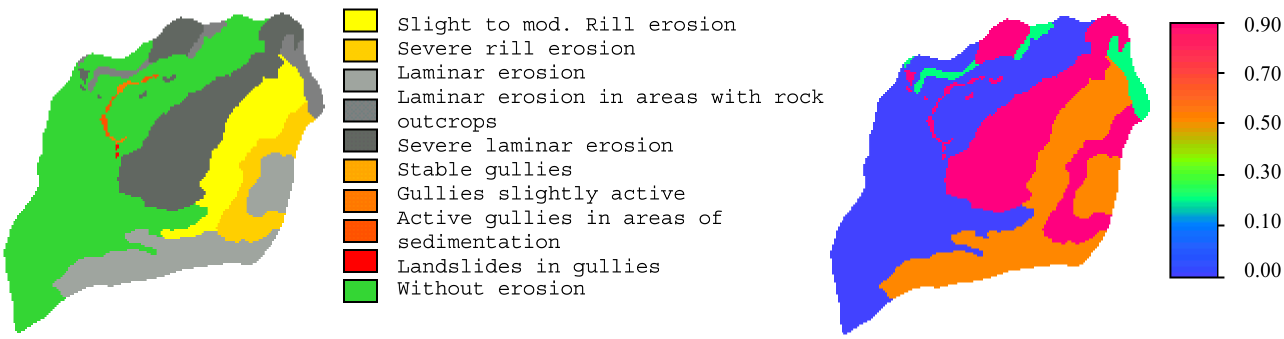
	Stability	Contribution to sedimentation	Predominant slope	Degradation Rate	Protection Rate	Membership Grade
Slight to moderate Rill erosion	0.5	0.5	0.5	0.3	0.5	0.5
Severe rill erosion	0.7	0.5	0.7	0.5	0.7	0.7
Laminar erosion	0.5	0.5	0.3	0.5	0.5	0.5
Laminar erosion in areas with rock outcrops	0.3	0.3	0.3	0.3	0.3	0.3
Severe laminar erosion	0.7	0.7	0.5	0.7	0.5	0.7
Stable gullies	0.3	0.3	0.3	0.1	0.3	0.3
Gullies slightly active	0.7	0.5	0.5	0.5	0.5	0.7
Active gullies in areas of sedimentation	0.9	0.7	0.7	0.9	0.7	0.9
Landslides in gullies	0.9	0.7	0.9	0.9	0.7	0.9
Without erosion	0.1	0.0	0.1	0.0	0.1	0.1

Stability:	Contribution to sedimentation:	Predominant slope:	Degradation Rate:	Protection rate:
0.1 - Stable	0.1 - No/very slight contrib.	0.1 - < 10%	0.1 - < 10%	0.1 - Very High
0.3 - Slightly unstable	0.3 - Slight contrib.	0.3 - 10 - 20%	0.3 - 10 - 20%	0.3 - High
0.5 - Moderately Unstable	0.5 - Moderate contrib.	0.5 - 20 - 35%	0.5 - 20 - 30%	0.5 - Moderate
0.7 - Unstable	0.7 - High contrib.	0.7 - 35 - 50%	0.7 - 30 - 50%	0.7 - Low
0.9 -Very unstable	0.9 - Very high contrib.	0.9 - > 50%	0.9 - > 50%	0.9 - Very Low

Table 1. Membership grades for erosion factors.

This means that the highest erosion risk membership grade should be selected to represent the map unit. In fuzzy set terms this means that a maximization fuzzy operator is needed, in other words Fuzzy OR. It assigns the highest value from the table. The fuzzy algebraic sum gives very extreme values and all results are classified about 0.8 to 1 and is therefore not useful. A satisfactory erosion risk map in relation to field validation was achieved and is shown in figure 3.

The approximation or evaluation of the membership grades can only be made based on expert experience. The sensitivity of the model in relation to the assigned membership grades depend on which fuzzy logic operator was select ed. If we deal with the OR operator it is sensitive to the maximum values and extra caution should be considered with assigning these values. The AND operator is most sensitive to the minimum values. When the Fuzzy algebraic product is applied it is useful if it does not consider too many maps. For example 0.8 * 0.4 = 0.32 but 0.8 * 0.4 * 0.5 = 0.16, so it can be seen that its application with more maps is strongly decreasive and all values calculated will be close to zero. On the other hand the same occurs but in the other extreme with the Fuzzy algebraic sum. When many maps are considered the sum will be strongly increasive and calculate all values close to 1. In most modelling cases we are not interested in the extreme values but in a more representative value. The combination method of fuzzy sum and product as well as the fuzzy factor gamma gives a useful solution in these cases. When these methods are applied a higher overall accuracy of membership grades is required.



Erosion Map   Membership Grades for Erosion Risk Map

Fig. 3 The creation of a Erosion Risk Map

The same methodology was applied to the geology-, geomorphology-, land use- and land cover maps. For each map the significant factors were determined and then reclassified by the Fuzzy set Operator AND (for minimization) or OR (for maximization). No fuzzy set was needed for the slope risk map in this case study because the slopes are very extreme. If the area were less steep, factors like slope aspect (convex and concave) and slope direction could be determined and with a fuzzy set operator converted in a slope risk map.

In this application a physical risk map has been created by combining the geologic (weight factor 0.3) and geomorphologic (weight factor 0.7) risk maps. The same process is applied to the land-use (weight factor 0.6) and land cover risk map (weight factor 0.4) to obtain one map concerning the natural land protection in relation to the land use.

The numerical value of the weight factor is a consideration based on expert experience in relation to the real field situation. It is clear that for example in a model with a few maps, in which a map A has a high weight factor close to 1 the reclassified value will be close to the value of map A.

The fuzzy set "combination" was selected as most appropriate. An advantage of this method is that the user can define weight factors to vary the importance of the input maps. Another advantage is that it does not calculate the extreme values. An example is given concerning the combination of the land use and land cover in figure 4.

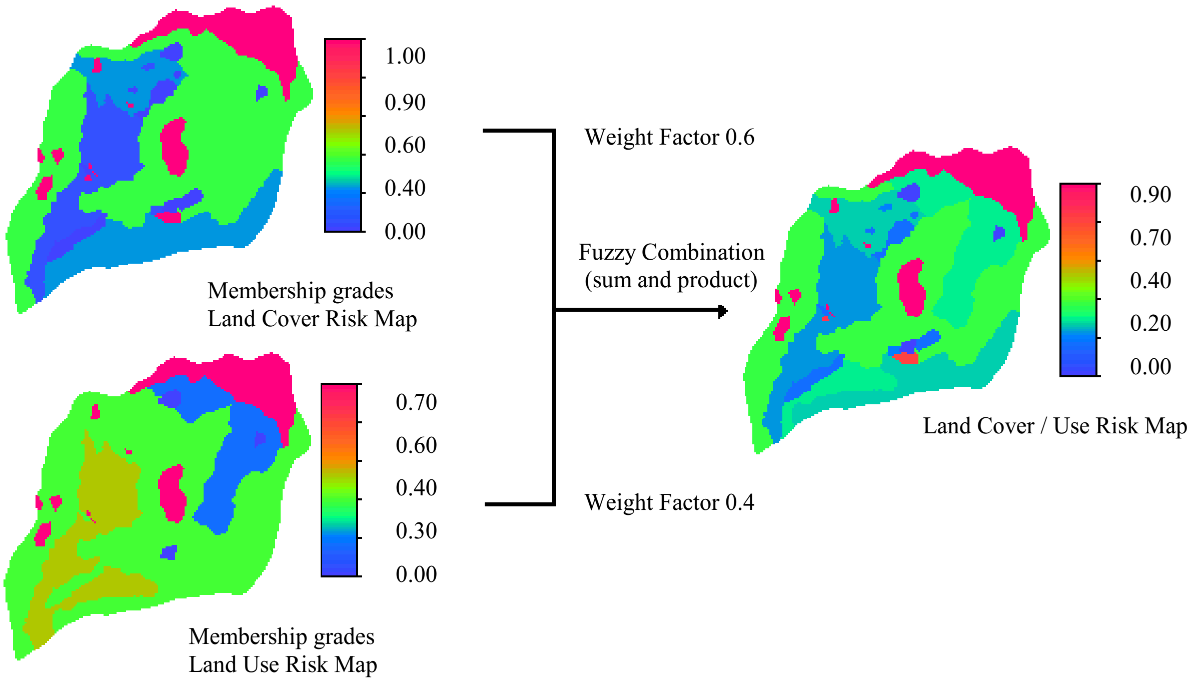


Fig. 4. Creation of the Land cover / use risk map

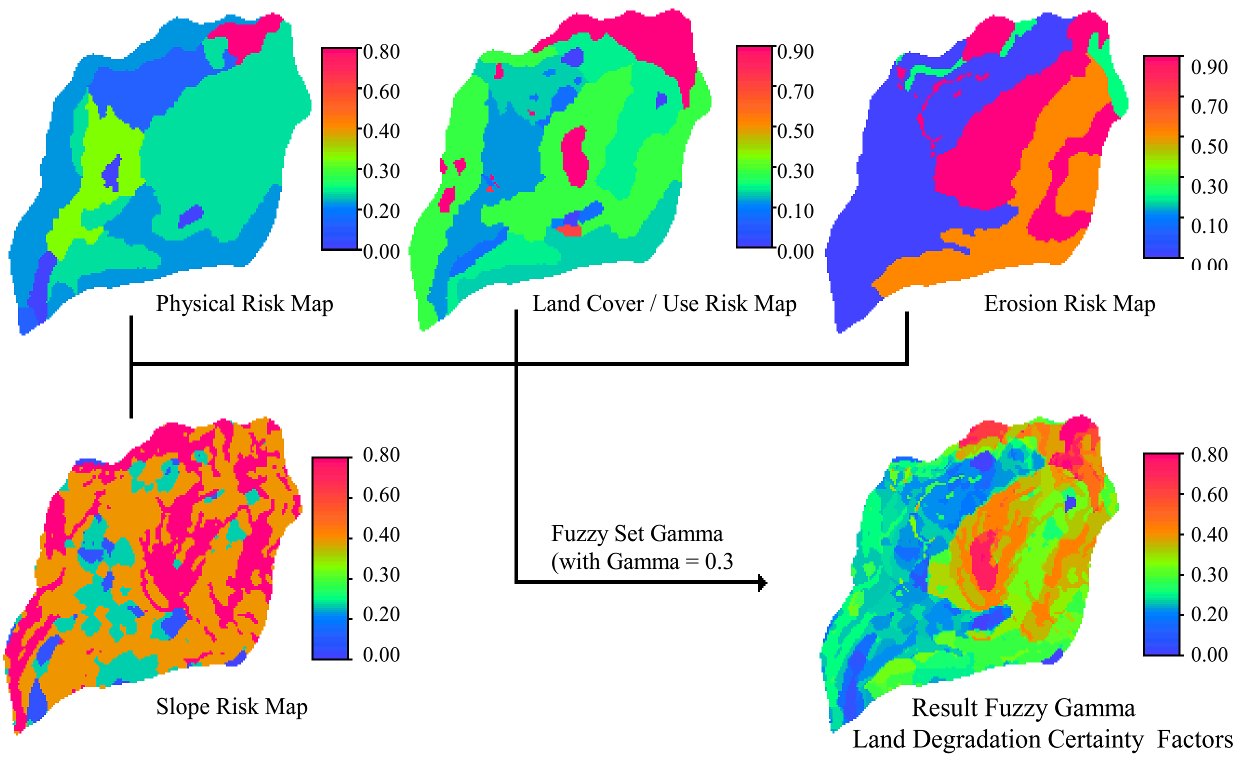


Fig. 5. Application of the Fuzzy Set Gamma to create the Land Degradation Risk Map

The final step is to combine the four risk maps containing their membership grades in relation to the land degradation hazard. The fuzzy set Gamma has been selected here because of its variable factor Gamma. The advantage is that the model can be validated in relation to reality by the gamma factor. Another option would have been the fuzzy set Combination because of its variable weight factors. In this case satisfactory results were obtained by the first fuzzy set mentioned. The best result of the land degradation risk was obtained with a gamma factor of 0.3. Using a greater gamma factor the land degradation was under-estimated and with a lesser value the land degradation was over-estimated. The value of the gamma factor depends on the expert experience and the real field situation. To determine the optimum gamma factor it is advisable to apply different gamma factors and select the one with its best representation. Figure 5 shows the combination of thematic risk maps by the Fuzzy Set Gamma.

The following example is the translation of the Fuzzy Gamma equation (with gamma = 0.3) in the Mapcalculation section of ILWIS2.23:

$$\mu c = \left(\prod_{i=1}^{n} \mu(x)\right)^{\gamma} \;*\; \left(1 - \prod_{i=1}^{n}(1-\mu(x))\right)^{1-\gamma} \quad \text{where } 0 < \gamma < 1$$

In ILWIS2.23:

pow(Physical*Landcov_use*Erosion*Slope,0.3)*pow(1-((1-Physical)*(1-Landcov_use)*(1-Erosion)*(1-Slope)),0.7)

Finally the land degradation risk map was reclassified (Fig. 6) It is easier to read a map with a legend low/ moderate/high and very high land degradation risk than values ranging from 0 to 1.The following reclassification groups were applied: 0 - 0.30 Low, 0.30 - 0.45 Moderate, 0.45 - 0.55 High and 0.55 - 1.00Very high).

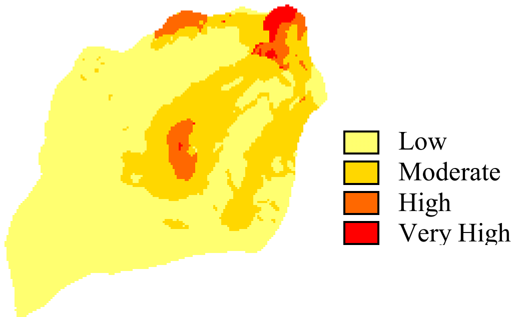


Fig. 6. Final Reclassified Land Degradation Risk Map

5 CONCLUSIONS

In this paper, the application of fuzzy set logic is presented for the modelling of natural resource processes in relation to geographic information systems. It is shown that fuzzy sets can be very useful when dealing with uncertainty, vagueness and complexity of data. It is very important to realise that the fuzzy logic analysis is based on expert knowledge and experience. This is clear, for example, in the choice of the fuzzy set operators, the values of the membership grades or certainty factors, the weight factors and the gamma factor. In any model related to Natural Resources fuzzy set logic is applicable. It is a subjective way of modelling and therefore it is very important that the final products are well calibrated and validated. In many cases the inference network will be a cycle of trying the model, readjusting membership grades, validating the results, and readjusting until a satisfactory result has been obtained.

In the Land degradation model a fuzzy logic analysis is demonstrated. The final product can be used for a zoning of priority intervention areas to reduce land degradation risk. We achieved a satisfactory method for identifying the land degradation risk for a catchment in the Andes. It is clear that the methodology is based on quite a lot of numerical membership grades or certainty factors but based on expert experience. The membership functions can be seen as the "knowledge base" and the inference network and fuzzy combination rules as the inference engine. Fuzzy logic is an important tool in expert systems where uncertainty of evidence is important.

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