Analytical Determination of Landslide Potential Using Fuzzy Sets and Other Statistical Techniques

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Abstract:

Recognizing the importance of identifying the potential slope instability, different methods have been developed by the experts in this field all over the world. However, because of the complex nature of this problem a method that is applicable to one region may not be applicable to another. Therefore, it is important to identify the causative attributes of landslides and accurately quantify their contribution in order to develop a methodology for a specific region. This paper presents a fuzzy set based integration system to access the landslide intensities, incorporating the studies made on Sri Lankan landslides.

Introduction:

Slope failures leading to significant loss of life and property have become a major threat to the economy of Sri Lanka. Therefore, every effort needs to be taken to accurately map the hazardous areas and develop modified infrastructure design and construction methods for these areas. Extensive landslide studies performed by the National Building Research Organisation (NBRO), Sri Lanka have identified factors such as (I) bedrock geology, (II) hydrology & drainage, (III) surface overburden, (IV) slope angle range, (V) land use, and (VI) land forms as major causative factors of Sri Lankan landslides (User Manual 1995). These factors contribute in different degrees to initiate a landslide, and in many occasions their impact is compounded (Bhandari et al. 1996). Therefore, the integration of the effect of such factors to evaluate the overall potential instability depends on how well their independent contribution is quantified.

NBRO currently uses a numerical evaluation system to assess the overall landslide hazard of a given site (User Manual 1995). As an input to NBRO's methodology, experts have established a set of subjective ratings, which can conveniently quantify the relative contribution of each causative factor. It is felt that these subjective ratings with their relative-weights can be more appropriately considered as fuzzy numbers, which can be included in fuzzy sets mathematical evaluation scheme (Ratnaweera et al. 1997 & Weerasinghe et al. 1999). The evaluation is based on a decision tree consisting of two levels identified as primary and secondary. It is assumed that attributes at primary and secondary levels have independent contributions on the hazard potential. The integration involves combining separate fuzzy numbers representing ratings and weights assigned to each causative factor or attribute at each nodal point of the above decision tree. For a given site, the integration results in fuzzy hazard potential which is then converted back to an appropriate linguistic scale containing 'very high', 'high', 'medium', 'low', or 'very low' designations, in order to illustrate the overall landslide potential of the site.

Once the overall hazard potential values are predicted for every site demarcated within the study area, they can be compared with the landslide intensities estimated for the same sites based on the available field data. The researchers expect to setup an iterative scheme whereby the initially assigned weights and ratings of the attributes can be adjusted until the predicted hazard potential matches with the landslide intensities identified in the field. This exercise is expected to result in more appropriate causative factor weights and ratings that would improve the accuracy of the hazard potential predictive capability.

Fuzzy Set Theory:

A fuzzy set of objects x is defined as a set of ordered pairs (Zadeh, 1965 and Cox 1994) and is expressed as:

$$I = (\mu(x), x) \qquad \text{(I)}$$

Where $\mu(x)$ is termed the "grade of membership of x in F', taking values in the closed interval [0,1]. A fuzzy object can be expressed in a discrete form or in the form of a mathematical function (i.e. shapes defined by standard π, S, β curves). When it is expressed in a discrete form containing a finite number of members:

$$I = \mu_I(x1)/x1 \cup \mu_I(x2)/x2 \cup \ldots \cup \mu_I(x_n)/x_n = / \mu(x)/x \qquad (2)$$

The symbol $\cup$ is used to represent the union operation, and the symbol / denotes the correspondence between an object in the set and its membership function.

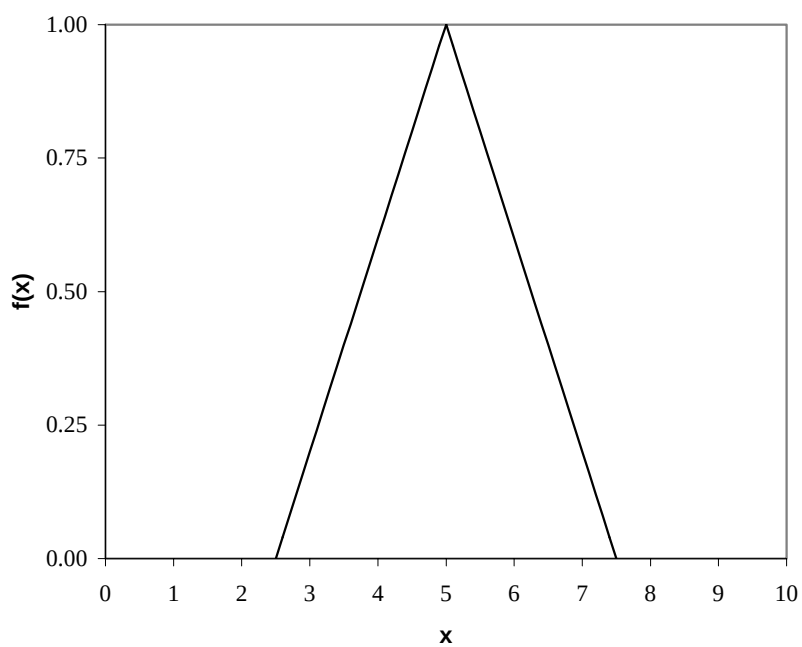

Figure 1: Fuzzy membership function of "about 5"

The fuzzy set "about 5", when expressed in a discrete form is given as (0.2/3, *0.6/4, 1/5,* 0.6/6, 0.2/7). Figure 1 expresses the same using a triangular membership function.

Extension Principle:
The extension principle provides the general extension of non fuzzy mathematical concepts to fuzzy environments such as the mapping of function *f* which maps a real number x onto y, i.e. $f{:}x \rightarrow y$ could be extended to map fuzzy numbers, i.e. if *I* is a fuzzy set, then $f{:}I \rightarrow f(I)$. From the extension principle, two inferences may be obtained and these are given below (Zadeh 1965, Cox 1994, and Gunaratne 1999).

Inferences: If C is a constant, then

$$C*\int \mu_I(x)/x = \int \mu_I(x) / C*x \qquad (3)$$

where ***** denotes one of the arithmetical operations of multiplication, addition, division or subtraction. If *f* is a relationship or a monotonic function that provides a mapping from x to y and is a fuzzy set expressed as $\int \mu_I(x)/x$, then

$$f(\int \mu_I(x)/X) = \int \mu_I(x)/ f(X) \qquad (4)$$

This equation states that the fuzzy set *1* that is denoted by function *f* can be deduced from the knowledge of the relationship of x under *f*.
Theorem: If *I*, *J*, and *K* are three fuzzy numbers and their membership functions are μ_I, μ_J, μ_K respectively, and if $K=I*J$ is the result of an arithmetic operation on the fuzzy numbers *I* and *J*, then the membership function of K is given by

$$\mu_K(z) = \vee \{\mu_I(x) \wedge \mu_J(y)\} \qquad (5)$$

where $\vee$ is the symbol used to indicate that the maximum should be selected from all possible values of the membership function, and $\wedge$ is the symbol used to indicate that the minimum should be selected from the possible values. Zero must not be a possible value of the fuzzy number **j** whenever the operations of division is involved.

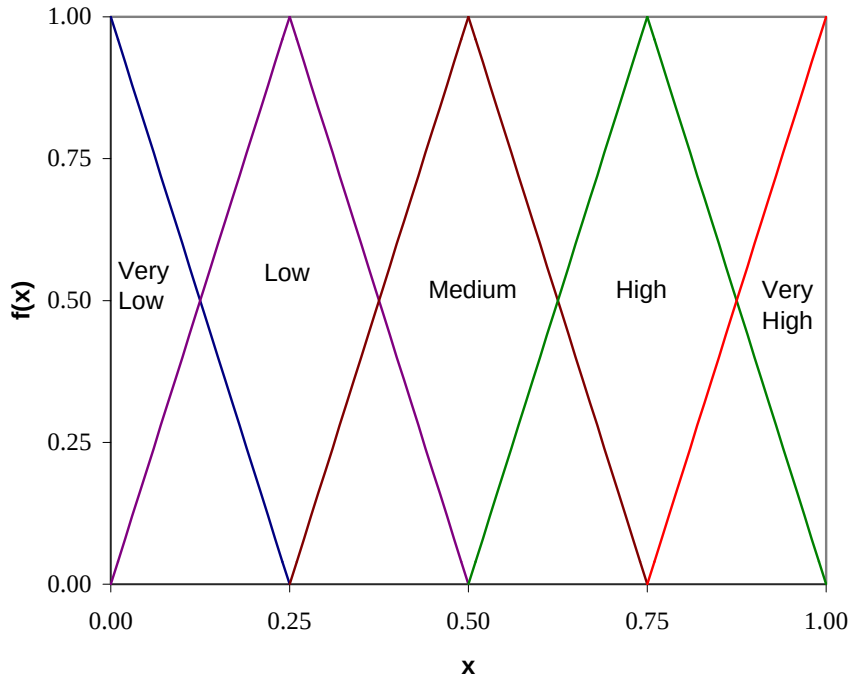

Figure 2: Fuzzy Membership Functions of five linguistic variables.

Evaluation Of Landslide Potential Using Fuzzy Sets:

As shown in Figure 3, the landslide hazard potential is evaluated based on a decision tree consisting of two levels identified as primary and secondary. Each level is identified by the node point at which branching takes place and it is assumed that the factors at primary and secondary levels, has an independent contribution towards the final result. The relative importance of each factor among the other factors that are connected to a node point of this tree is indicated by a linguistic value and are shown within parenthesis against each factor. Table 1 converts these linguistic values into subjective weights or ratings.

Linguistic Value	Relative Importance/Severity
A	Very High
B	High
C	Medium
D	Low
E	Very Low

Table1: Conversion of linguistic values into subjective ratings or weights.

Fuzzy integration involves combining of membership functions representing ratings and weights. These functions are first normalised to the domain ranging between 0 to 1 and are expressed in terms of a linguistic variable.

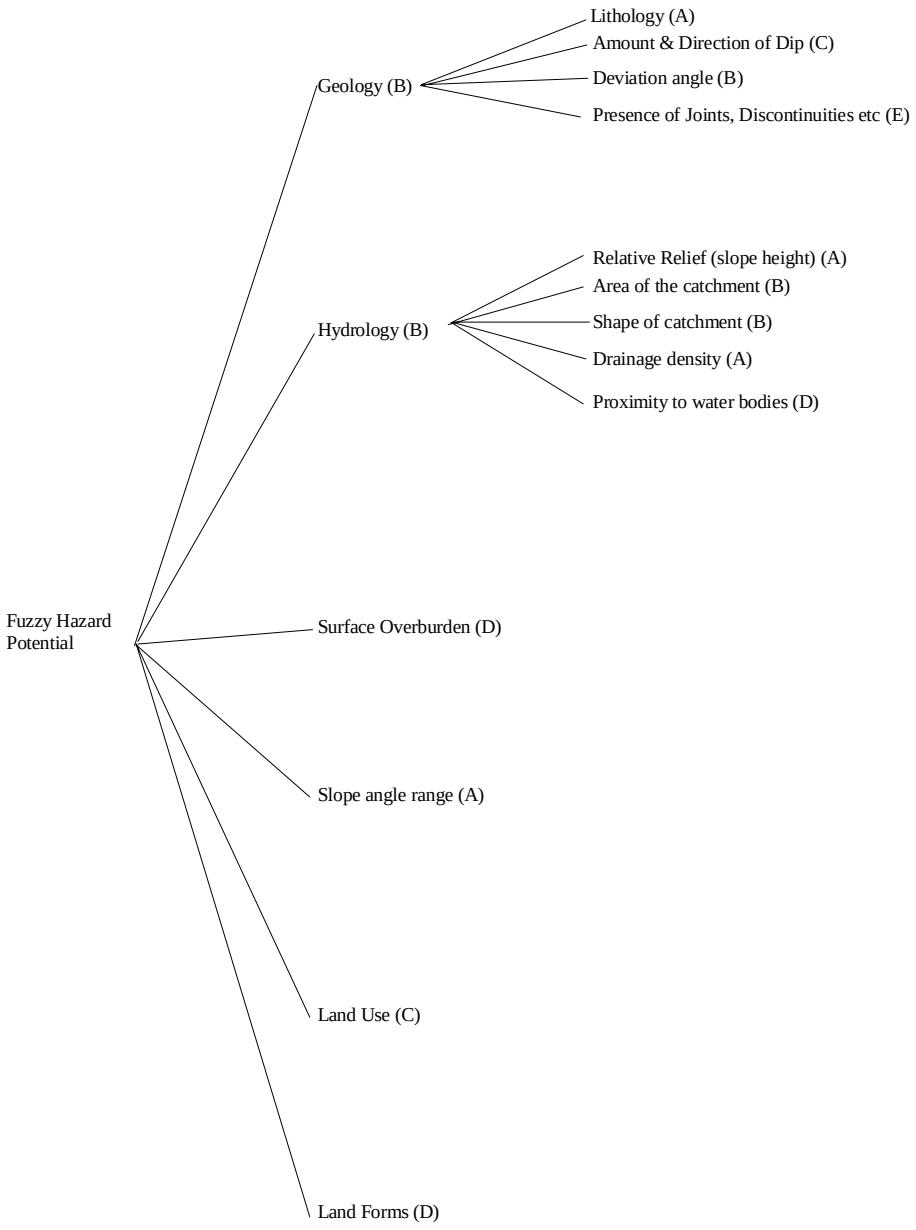

Figure 3: Decision tree used for evaluation of fuzzy landslide hazard potential.

The combined rating of the failure potential, *R*, based on a weighted average of all factors on a given branch of the evaluation tree is expressed as:

$$R = \left[\prod_{j=1}^{n} (r_j)^{w_j} \right]^{\beta}$$

(Juang et al., 1992.) (6)

where, r_j is rating of failure potential according to factor j; w_j is weight of factor j as compared with other factors on the same branch of the evaluation tree; n, number of factors in the given branch of the evaluation tree, and

$$\beta = \frac{1}{\sum_{j=1}^{n} w_j}$$

(Juang et al., 1992.) (7)

The overall fuzzy distribution function is obtained by using the same approach, repeatedly, at each level of the decision tree. This can be directly evaluated using conventional arithmetic using the extension principle and its inferences (equations 3 through 5) or by using the Monte Carlo Simulation Technique as suggested in Juang et al., 1992.

Methodology:

For a given area, a preliminary hazard map is prepared by overlaying the state-of-nature maps of geology, hydrology, surface overburden, slope range, land use, and land forms (Figure 4). The subjective ratings identified using linguistic terms are stored in a Geographic Information System Database along with this preliminary hazard map. The analysis as discussed above is performed to integrate the linguistic ratings representing the primary/secondary factors and their weights for each polygon of this map. For a given site, the integration results in fuzzy hazard potential which is then converted back to an appropriate linguistic scale containing ‘very high’, ‘high’, ‘medium’, ‘low’, or ‘very low’ designations, in order to predict the overall landslide potential of the site (Figure 5). This conversion is performed based on the Euclidean distance method as expressed in Lee et al. (1992)

Once the hazard potential values are predicted for every zone demarcated in the study area, they are compared with landslide intensities estimated for the same zones based on available field data (Figure 5). Then, through an iterative scheme whereby the initially assigned weights and sub-weights of the relevant attributes are systematically adjusted until the field data corroborates the predicted hazard potential at a satisfactory level, in all of the zones.

Conclusion:

The discussed method provides a cost effective analysis and mapping of landslide potential in the mountainous areas in Sri Lanka. This methodology also enables to input subjective and fuzzy evaluation of hazard by the human, while requiring less expertise on the subject.

With further comparison of actual field landslide intensities, the researchers expect to adjust the initially assigned weights and ratings of the attributes until the predicted hazard potential matches with the landslide potential identified in the field. This exercise is expected to result in more appropriate causative factor weights and ratings that would improve the accuracy of the hazard potential predictive capability.

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