

Fuzzy logic application in compiling multi geohazards macro-zone maps; case study: Rahdar, 1:25,000 Quadrangle, Khuzestan, Iran

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Abstract This paper is devoted to describe a new method of fuzzy logic applied to multi geohazards macro-zone maps. The basic steps are (1) compilation of macro-zone maps for each type of geohazard phenomenon. Each phenomenon is then assigned one of seven geohazard zones: very low, low, relatively low, moderate, relatively high, high, and very high; (2) definition of a membership function using a fuzzy logic algorithm to quantify the qualitative data, estimate a geohazard grade for each mesh point, and to convert qualitative maps to quantitative maps; (3) computation of the summed hazard grade for each mesh point and creation a cumulative geohazard map; and (4) compilation of a multi geohazards macro-zone map by defining a mathematical algorithm and again using fuzzy logic. The paper also describes a mechanism that takes subjective engineering judgments into account. Finally, a geohazard map with a scale of 1:25,000 (Rahdar district, Khuzestan, Iran) is compiled. This study divides the area into seven geohazard macro-zones. Zones of high and very high geohazard classification cover most of the area due to the large number of sinkholes and asymmetric subsidences, rock falls and other slop movements. Low and very low hazard zones only cover small localities.

Keywords Fuzzy logic application · Multi geohazards macro-zone maps · Rahdar · Khuzestan, Iran

Introduction

Geohazards are naturally occurring hazards on the Earth's surface that place both natural and man-made objects in danger. Some of the most severe hazards include landslides, rock-

falls, hillside collapses, erosion and water washing in various facets, asymmetric subsidences, sinkholes, creep, liquefactions and large-scale ground failures. There are also some hazards that stem from a combination of land and atmospheric effects, such as floods and avalanches. (It should be noted that from the viewpoint of ground acceleration in bedrock, the role of earthquakes was studied separately but is still taken into the account when compiling the above-mentioned maps.)

These hazards can cause destruction to farm fields and hillsides, as well as man-made features such as buildings, roads, canals, water mains and networks, and the electricity distribution network. Severe instances can cause casualties as well. Therefore, specifying each phenomenon and creating maps of their locations is an effective strategy toward sustainable development of the affected lands. Creating a multi geohazards macro-zone map that includes all possible geohazard phenomena is imperative as well.

Multi geohazards macro-zone maps must take into account all hazards in nature. Because of the variety of hazards, it is unwieldy to show macro-zones for all of the individual geohazard phenomena in a single map. Also, absolute quantification of the mentioned hazards using Boolean logic of one and zero is not the most productive method to compile such maps. It is more productive to use fuzzy logic to describe each hazard qualitatively or, better yet, quantitatively within a scaled range (and not an absolute value). Fuzzy logic is also best suited for identifying non-sharp boundaries which lack clear definition, which is often the case when studying geohazard phenomena. In this article, we outline an approach to identify and to map geohazard macro-zones using fuzzy logic.

Fuzzy logic

Classical mathematics adopts a binary attitude toward subjects; for example, a variable either has a specific value or it does not.

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From this point of view, an answer to a question is either true or false; there is no compromising position. In reality, however, there are some phenomena where it is more suitable to adopt a continuum of answers between two extremes. This attitude toward understanding phenomena is described by the term fuzzy logic, as presented by Zadeh in 1965.

Fuzzy set theory as formulated by Zadeh (1965, 1978) differs from the traditional Boolean set theory in the way that an object's membership is defined within a set. In a traditional set, an object is either completely in the set (a degree of membership of 1) or it is not in the set (a degree of membership of 0). However, the degree to which an object is a member of a fuzzy set can have any value between 0 and 1. Mathematically, a fuzzy set S , out of total pixels A , is defined as a set of ordered pairs given as:

$$S = \{(p, \mu_s(p)) | p \in A\} \quad (1)$$

Where S is a collection of objects and $\mu_s(p)$ is called the membership function or the degree of compatibility of p in S . In other words, $\mu_s(p)$ in Eq. (1) specifies the extent to which p can be regarded as belonging to S . Every value of p is associated with a value of $\mu_s(p)$, and the ordered pairs $[p, \mu_s(p)]$ are known collectively as fuzzy sets. The range of $\mu_s(p)$ is typically defined from $[0,1]$, where 0 expresses non-membership and 1 expresses full membership. With respect to a given data set (a thematic map), a membership can be assigned to each map category according to its direct or indirect relationship with the phenomena under consideration. In our case, the criteria is the presence and absence of a landslide or other form of mass ground movement.

The most important aspect of a fuzzy logic analysis is assigning fuzzy membership values (again ranging from 0 to 1), but unfortunately there are no practical constraints on the choice of these values. Values are simply chosen to reflect the degree of membership of a set, based on subjective judgments as shown by Bonham-Carter (1994) for mineral exploration, or they can be derived by various functions representing reality, such as “J-shaped,” “Sigmoidal,” and “Linear functions” (IDRISI 1995). These values can be either user-defined, derived from information (Yin and Yan 1988), or obtained through an analytical hierarchical process (Saaty 1978).

Using fuzzy logic to study geohazards can be both effective and beneficial, since drawing a sharp boundary between danger and safe areas is usually not possible. However, one needs an easy, comprehensible and operational approach to creating such geohazard maps. One of the defining features in fuzzy theory is the membership function and its definition. There is no distinct algorithm that can be used to obtain the membership function; rather it is obtained through the author's experience, innovation, and personal ideas. For geohazards, we will use the weights of each hazard.

Fuzzy logic has been applied by many researchers to the fields of mining, geology, and other geotechnical studies (Rao and Prasad 1982; Van Westen 1993; Chung and Fabbri 1993; Chung et al. 1995; Carrara et al. 1995; Champati ray 1996; Taboada et al. 2006). In this study, our fuzzy logic approach is based on the knowledge representations and the flexibility of fuzzy integration methods of Champati ray (1996, 2004) and Chung and Fabbri (1993).

Geohazards and relative macro-zones

In order to plan sustainable use of land, it is important to specify relative hazard zones. This can be accomplished by creating macro-zone maps that combine the presence of the earlier-mentioned hazards with the different rates appropriate for each hazard. Both the hazard type and hazard rate are important. Subsequently, since the map presents all types of geohazards, it plays a significant role when deciding on land-use. Since we cannot quantify absolute hazard rates, adapting relative hazard rates is the logical path to follow.

Macro-zoning selection using relative hazards

When creating geohazard maps, specifying and separating the macro-zones with different relative hazard rates should be accomplished based on the map's scale. A practical scheme using relative hazard rates is needed that can cover all of Iran. Along these lines, we define seven relative hazard macro-zones as follows (in decreasing order of severity): very low, low, relatively low, moderate, relatively high, high, and very high.

Methodology

The method we apply is as follows:

1. Macro-zone maps are compiled for each geohazard phenomenon.
2. A membership function is defined using a fuzzy logic algorithm to quantify the qualitative data.

Table 1 Macro-zonation numbering

Macro-zone	n
Macro-zone with very low relative hazard rate	1
Macro-zone with low relative hazard rate	2
Macro-zone with nearly low relative hazard rate	3
Macro-zone with average relative hazard rate	4
Macro-zone with nearly high relative hazard rate	5
Macro-zone with high relative hazard rate	6
Macro-zone with very high relative hazard rate	7

Table 2 Main and minor weights computed for various macro-zones

No	Relative geohazard rate		Main weight	Minor weight
1	Macro-zone with very low	Relative hazard rate	0	0
2	Macro-zone with low	Relative hazard rate	1	0
3	Macro-zone with relatively low	Relative hazard rate	2	0
4	Macro-zone with moderate	Relative hazard rate	4	±1
5	Macro-zone with relatively high	Relative hazard rate	8	±2
6	Macro-zone with high	Relative hazard rate	16	±4
7	Macro-zone with very high	Relative hazard rate	32	±8

- Summation values are computed for the individual hazard grades at each mesh point, and a cumulative geohazard map is compiled.
- A multi geohazards macro-zone map is created by defining a mathematical algorithm and using the fuzzy logic method.

Compilation of macro-zoning maps

Macro-zoning maps were compiled for each geohazard phenomenon such as landslides, rock falls, sink holes, asymmetric subsidences, liquefactions, erosion and water washing in various situations, large-scale ground failures, floods, avalanches, etc. The seven geohazard zones as outlined above were used to qualify the relative hazard rates.

Definition of a membership function and quantizing macro-zoning maps

In order to compile the applied maps and to illuminate the stages of mapping, it is necessary to explain each hazard component either quantitatively or semi-quantitatively. For this work, we follow the approach outlined below. First, each macro-zone is numbered (*n*) as follows in Table 1.

Second, a membership function is defined by

$$H_n = f_n + f'_n \tag{2}$$

Here, *n* represents a number from 1 to 7 and *f_n* is the main weight of each macro-zone calculated by

Table 3 Final geohazard macro-zone using summed hazard component weights

<i>H_C</i>	Relative hazard	
0–2	Macro-zone with very low	Relative hazard rate
3–5	Macro-zone with low	Relative hazard rate
6–9	Macro-zone with relatively low	Relative hazard rate
10–14	Macro-zone with moderate	Relative hazard rate
15–23	Macro-zone with relatively high	Relative hazard rate
24–40	Macro-zone with high	Relative hazard rate
>40	Macro-zone with very high	Relative hazard rate

$$f_n = 2^{n-2}. \tag{3}$$

For macro-zone number 1, the value of *f_n* is defined to be zero. The minor weight of each macro-zone, *f'_n*, is then calculated by

$$f'_n = \pm 2^{n-4} \tag{4}$$

The minor weights of macro-zones numbers 1, 2, and 3 are defined to be zero. For the other macro-zone numbers, the minor weights span a range of numbers. For example, for macro-zone number 6, the possible minor weights are -4, -3, -2, -1, 0, 1, 2, 3 or 4 according to Eq. (4). Minor weight components for each macro-zone are determined based on the hazard’s specific details and general engineering judgment. Therefore, a range of values are given to each macro-zone such that macro-zones with higher relative hazards have wider ranges.

According to the discussion above, the main and minor weights for each macro-zone are given as follows in Table 2.

Using this method, it is possible to convert the qualitative macro-zoning maps for each geohazard to its corresponding quantitative macro-zone map.

Computing geohazard sum values and compiling the cumulative geohazard map

After creating individual quantitative macro-zone maps for each hazard, we combined the maps to obtain a resultant map including all geohazard phenomena. Throughout this process, as usual when using fuzzy logic, engineering judgment plays a major role. We superposed the independent maps and determined the cumulative hazard rate at any desired mesh point according to

$$H_C = \sum_{i=1}^m H_i \tag{5}$$

Where, *m* is the total number of hazard causes (rock fall, water washing, flood, creep, etc.) *H_i* is the hazard rate for each cause (slide, rock fall, etc.) acquired in the previous step and *H_C* indicates the total cumulative hazard rate in a specific location.

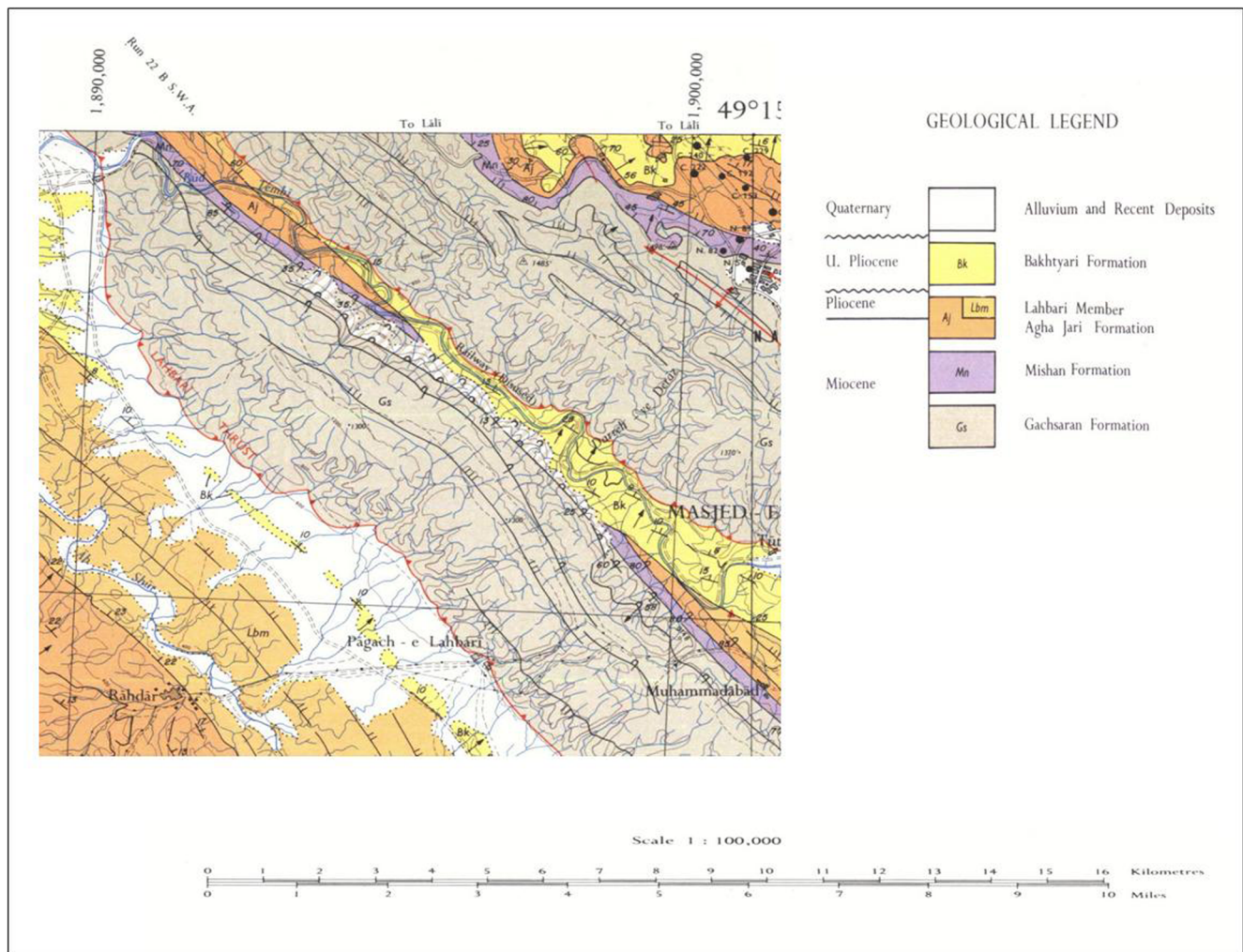


Fig. 1 Geological map of Rahdar region

Relative geohazard hazard macro-zoning map

A digital map is created after computing H_C values for each mesh point in a specific area. This map is then converted to a relative hazard macro-zone map that includes all geohazard phenomena. In such a map, the area of interest is divided into

macro-zones based on H_C , where H_C can vary from zero to over 40. The geohazard macro-zones are identified based on the H_C values as given in Table 3.

The role of every geohazard (such as landslide, rock fall, etc.) in the macro-zone map can be described by fuzzy logic. For example, if in a zoned landslide hazard is very high during a

Fig. 2 An example of rock fall in the Aghajari formation



Fig. 3 An example of sinkholes in alluviums



short time interval (say during periods of rainfall), then landslides could result and this zone should be classified as a relatively high hazard zone even if other geohazards are unlikely. That is to say, the landslide's role in such a macro-zone is so significant that the absence of other geohazards does not weaken the hazard rating.

Normalizing the values to the fuzzy set theory

As it is well-known that in the fuzzy set theory, a membership function determines the truth values, which elements of a domain belong to a fuzzy set with values from 0 to 1.

In the presented method, we are faced to some truth values (in fact natural numbers). If we want to convert these values to a normal fuzzy logic set, we can divide the H_C values by 50. In this case, the formula (5) would be a normal membership function of a fuzzy set and the H_C values would have a rate of 0 to 1. For example, for a very low hazard zone the H_C would be 0–0.04 and it would be more than 0.80 for a very high hazard zone.

Fig. 4 An example of rill washes in alluviums



Any way, it is not necessary convert the values to a 0–1 rate. We recommend no any conversion of the values when applying this method.

Case study: the Rahdar Quadrangle 1:25,000 (Khuzestan, Masjed Suleiman)

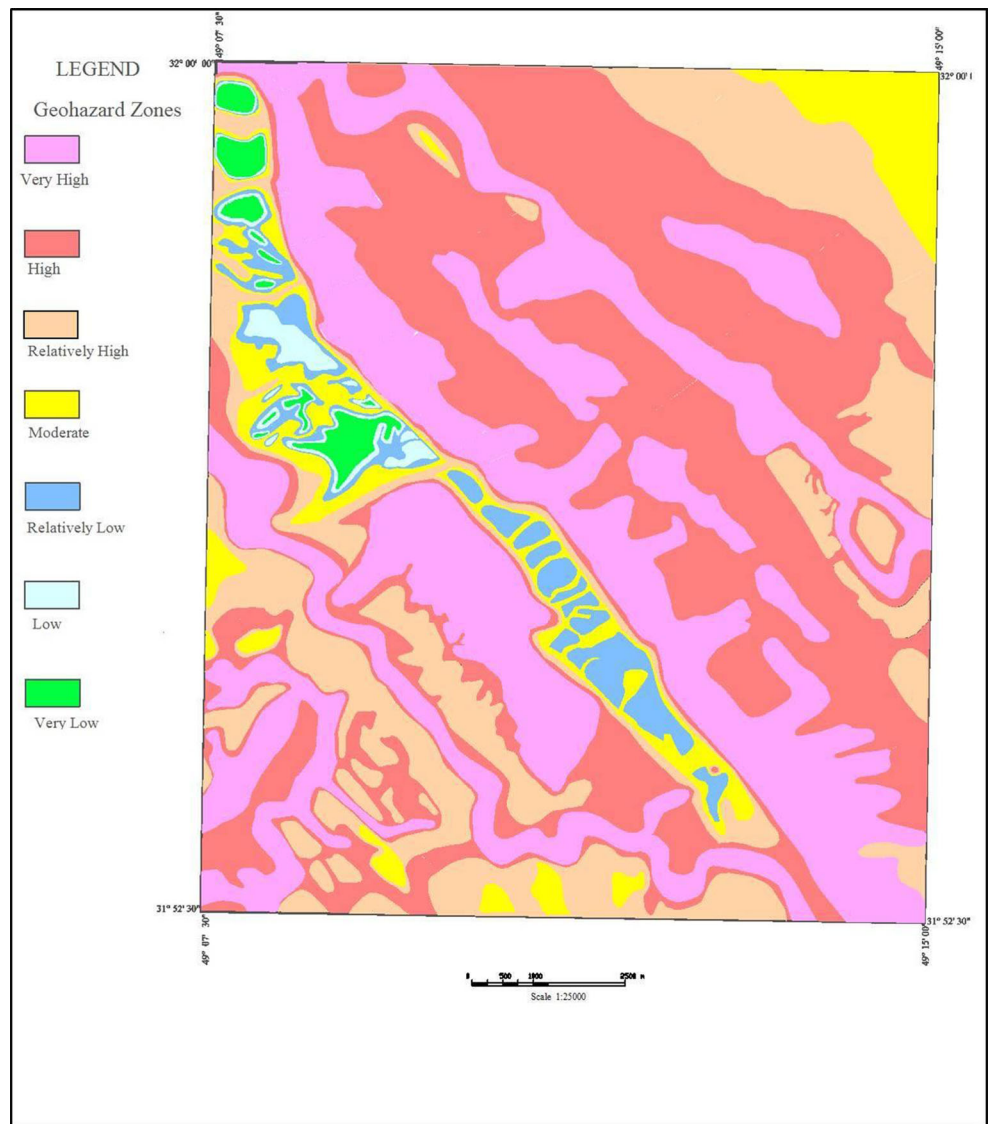
The Rahdar area is defined by the geographical coordinates $49^{\circ}7'30''$ to $49^{\circ}15'00''$ east and $31^{\circ}52'30''$ to $32^{\circ}00'00''$ north in west Masjed Suleiman, southwest Iran (Fig. 1). The Masjed Suleiman region is famous for existing oil and gas fields. From a geological point of view, this area is covered by sedimentary rocks and alluvium deposits (Ramazi 2007). Geological formations along a southwest to northeast cross section are as follows:

Aghajary formation: composed of hard sand stones and soft marls. Bedding dip is approximately 50° toward the northeast. The most important geohazard phenomenon in this area is rock falls (Fig. 2) and the second-most important is localized landslides (Ramazi 2007).

Fig. 5 A small bridge destroyed because of rill wash



Fig. 6 Multi geohazards macro-zoning map of Rahdar region



Lahbari formation: mainly Marls and clay stones, with a dip direction the same as the Aghajari formation but shallower. Topography is more or less smooth with small-scale slope movements as the primary geohazard phenomenon (Ramazi 2007).

Bakhtyari formation: conglomerate, low dip bedding. This formation has small outcrops in the studied region without any significant geohazard phenomena (Ramazi 2007).

Alluvium and colluvium formation: composed of silt, gypsum, clay, and gravel, smooth topography. Sinkholes and rill washes are main geohazards in this formation (Figs. 3, 4, and 5) (Ramazi 2007).

Gachsaran formation: the main element of this formation is gypsum, but also contains some clay. Two large areas of the studied region are covered by the Gachsaran formation. Topography is sharp and sinkholes and rock falls are the main geohazard phenomena (Ramazi 2007).

Mishan formation: a relatively thin formation mainly composed of limestone with a steep layer dip. Rock slides are observed in several places (Ramazi 2007).

We used the methodology outlined above and compiled a relative multi geohazards macro-zone map (scale of 1:25,000) of the Rahdar area (Fig. 6). As seen in the map, most parts of the studied area have either high or very high geohazard classifications.

Conclusions

The most important results are summarized as follows:

Fuzzy logic is an effective way to specify geological hazards, as opposed to a more binary approach of classifying a zone as simply a hazard or not.

The presented method is a mathematical one which can easily convert the qualitative expressions to quantitative ones.

Given the exponential form of Eq. (3), there is a remarkable difference in weights of high and very high relative hazards in comparison with the other relative hazards. Thus, if a single hazard (such as a landslide) has a very high relative hazard, then even if the other hazards are not severe, this area's place in final map will still be high or very high. This approach seems logical.

The presented method has been formulated in a way that the hazard weights follow gradual changes in the

final macro-zone map, in harmony with gradual changes observed in natural phenomena.

There is some role of subjective engineering judgments in the presented approach, but it is not so crucial as to significantly change the final hazard factors.

The method is simple, easy and practical.

This method was successfully used to create a 1:25,000 scale macro-zone hazard map of the Rahdar area.

From a geohazard point of view, most places of the studied area are located on very high or high hazard zones.

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