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Neutrosophic K-means for the analysis of earthquake data in Ecuador

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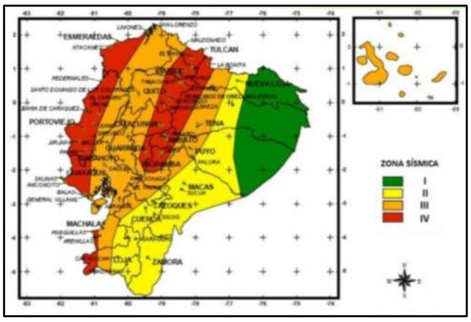
Abstract. The occurrence of earthquakes may have catastrophic and devastating consequences for the inhabitants of the place where they occur. Some regions are characterized by the high frequency of this type of natural phenomenon. Such is the case of Ecuador, a country with a high seismic index due to its location in a subduction zone between the Pacific Plate and the South American Plate. Predictions in the behavior of earthquakes are a way of prevention that allows taking measures according to vulnerability. Although it is difficult to accurately predict the occurrence of an earthquake, there are dissimilar types of analysis to observe its behavior and patterns of occurrence. The nature of earthquakes and their monitoring variables usually make up large databases. For its processing and subsequent analysis of the results, it is convenient to use statistical techniques of Data Mining such as K-Means. In this work, the classic K-Means method is combined with Neutrosophy to improve the results obtained by taking into account the indeterminacy of such complex data sets and including the diversity of the data and its fluctuation, due to the proximity among the boundaries and their membership clusters.

Keywords: K-means clustering, Neutrosophy, earthquakes, prediction, vulnerability

1 Introduction

Due to the devastating effects of earthquakes, society has needed to predict their behavior as a way of prevention [1]. Such is the case of Ecuador, which has a high seismic index due to its location in a subduction zone between the Pacific Plate and the South American Plate, known as the Pacific Ring of Fire. Statistics show that there is a high probability of a major earthquake every 40 years. In other words, if a person lives permanently in the country, he has a high possibility of experiencing at least two major earthquakes during his life, as illustrated in Figure 1[1-3]. This situation, linked to the unfavorable economic indicators that this country has, enhances the negative effects of the phenomenon.

The ability of a disadvantaged population to recover from an earthquake is affected by limited economic and political capital [4]. Numerous studies examining social vulnerability use quantitative indices often modeled with census data to illustrate to governments the need for predictive studies and improvement of quality of life. The imminence of suffering the consequences of a big natural disaster prompts researchers to improve the living conditions of residents in the country by studying their behavior [2, 4-15]. That is why an infrastructure of equipment has been installed to achieve the best possible follow-up of the events.[16] (Figure 1).



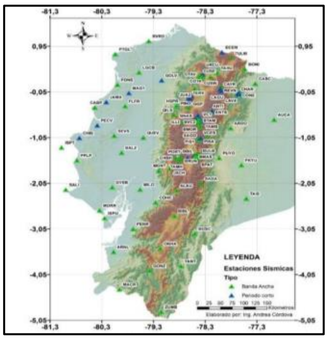


Figure 1. Seismic risk in Ecuador [3] and network of seismic stations [16].

Predictions in the behavior of earthquakes are a form of prevention that contributes to the right to life as part of the human rights of Ecuadorians. Although it is known that it is difficult to accurately predict the occurrence of an earthquake, there are dissimilar types of analysis that range from the behavior of variables and their patterns to the identification of vulnerabilities as illustrated in Figures 2 and 3 [1-3, 13, 14, 17]. Due to its heterogeneous nature, analyzing earthquakes combines statistics and probabilistic with decision-making methods that integrate multiple data sets [2, 11, 13, 18]. The choice of evaluation criteria has been different since the multicriteria evaluation was adopted as a problem-solving and decision-support tool[15, 19].

Jan	Feb	Mar	Apr	May	Jun
40	21	25	35	20	17
Jul	**Aug**	**Sep**	**Oct**	**Nov**	**Dec**
21	16	16	30	20	27

Figure 2. Seismic activity in Ecuador 2020 [16].

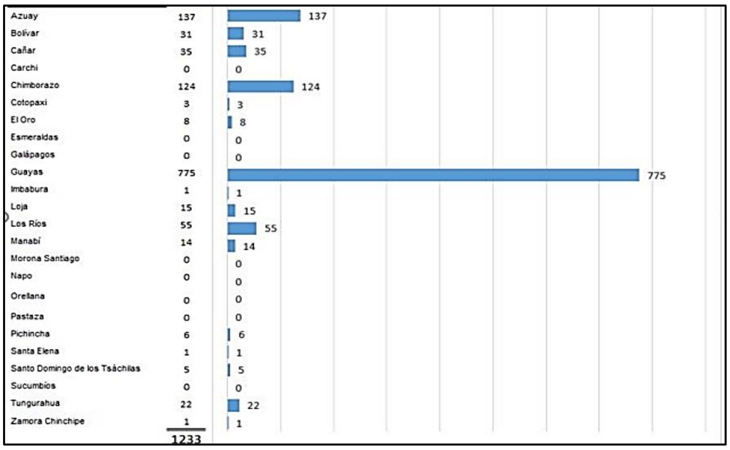


Figure 3. Histogram of earthquake occurrences in 2021 by province [17].

There are studies focused on geophysical factors[20-22]; some other have integrated social vulnerability [23, 24]; but all converge on the need to provide strategies for action. In general, they facilitate simple unit comparisons that can be used to illustrate the complexity of dynamic environments in wide-ranging fields. Despite their heterogeneity, they all expose the possibility of predicting behavior to predict actions by combining criteria of different natures and requires a series of steps in which decisions must be made.[25-27]. This enables preparation and response programs to reduce the negative impacts of these natural disasters.[3, 15, 17].

These phenomena are variable, but within their unpredictability, patterns are sought that achieve proactivity and fulfill the right to life of residents in Ecuador. [1]. Therefore, the objective is focused on applying data segmentation methods (clustering) to a dataset with information on earthquakes in Ecuador to analyze common characteristics in the resulting clusters and to be able to use these results for predictive purposes. From now on, to comply with the aforementioned, the following specific objectives are formulated:

1. Analyze the data contained in the dataset.
2. Apply the neutrosophic K-means clustering technique.
3. State detected patterns

This study is intended to contribute to the early detection of earthquakes that enables adequate preparation and mitigates their adverse effects on the lives of Ecuador's residents and therefore their quality of life, after the disaster.

2 Methods

The nature of earthquakes and their monitoring variables usually make up a large database (big data or dataset) that constitutes a source of knowledge to be used by researchers. For its processing and subsequent analysis of the results, it is convenient to use statistical techniques of Data Mining such as K-Means. Currently, due to the spatial variations of its components, it is significant to include the treatment of uncertainty [2, 11, 13, 14, 18, 20-24]. Therefore, the analysis is made up of the K-Means statistical technique in its Neutrosophic version, because it will take into account the uncertainties and the uncertainty environment inherent to the predictions. The use of a Neutrosophic K-Means based on the classical algorithm is appropriate due to the efficiency demonstrated for the decision-making process based on interpretation of the linguistic terms provided by Neutrosophy and its ability to deal with uncertainty.

2.1 Classic K-Means

According to what was stated by [15, 28-38], the K-Means technique is frequently used in Data Mining, due to its ease in handling and classifying large amounts of data through clustering or grouping. According to [39], clustering means grouping things that are similar or have features in common, and so is the purpose of k-means clustering. K-means clustering is an unsupervised machine learning algorithm for clustering 'n' observations into 'k's clusters where k is a predefined or user-defined constant. The main idea is to define k centroids, one for each cluster. The K-Means algorithm involves:

1. Choosing the number of clusters "k".
2. Randomly assign each point to a cluster.
3. Until clusters stop changing, repeat the following:
   - For each cluster, compute the cluster centroid by taking the mean vector of points in the cluster.
   - Assign each data point to the cluster for which the centroid is the closest.

Two things are very important in K-means, the first is to scale the variables before clustering the data, and the second is to look at a scatter plot or a data table to estimate the number of cluster centers to set for the k parameter in the model.

2.2 Notions of Neutrosophy

Neutrosophy is a new branch of philosophy that studies the origin, nature, and scope of neutralities created by Professor Florentin Smarandache. Its incorporation guarantees that the uncertainty of decision-making is taken into account, including indeterminacies where experts will issue their criteria evaluating linguistic and non-numerical terms, which constitutes the most natural form of measurement in human beings.[33, 40-64]. Logic and neutrosophic sets, for their part, constitute a generalization of Zadeh's fuzzy logic and sets, and especially of Atanassov's intuitionist logic, with multiple applications in the field of decision-making, image segmentation, and machine learning.[40, 42, 65, 66].

Definition 1 [42, 67, 68]: Be X a universe of discourse, a Neutrosophic Set (CN) is characterized by three membership functions,$\mathrm{u_A(x)}:, \mathrm{r_A(x)}:, \mathrm{v_A(x)}:: \mathrm{X} \rightarrow \;]^{-}0, 1^{+}[$, which satisfy the condition -0 $\leq$ $\inf \mathrm{u_A(x)} + \inf \mathrm{r_A(x)} + \inf \mathrm{v_A(x)} \leq \sup \mathrm{u_A(x)} + \sup \mathrm{r_A(x)} + \sup \mathrm{v_A(x)} \leq 3$ + x$\subset$X $\forall \mathrm{u_A(x)}, \mathrm{r_A(x)}$ Y $\mathrm{v_A(x)}$: denote the membership functions of true, indeterminate, and false of x in A, respectively, and their images are standard or non-standard subsets of $]^{-}0, 1^{+}[$.

2.2 Neutrosophic K-means

According to the bibliography consulted [33, 35, 69-71], the Neutrosophic K-Means is an extension of the classic K-Means, as a neutrosophic data mining technique for clustering. This variant is useful to automatically manipulate databases provided by the Ecuador earthquake network in the prediction process. The algorithm allows exploring, organizing, and segmenting large amounts of data, detecting consistent behavior patterns or relationships between the different variables to apply them to new data sets.

This analysis includes the diversity of the data and its fluctuation since due to the proximity of the limits between them and the clusters they belong to, it is difficult to identify them, resulting in false conclusions and the existence of contradictions due to the uncertainty that this may generate. Based on what was stated by [72] the method consists of assigning to each data a value or degree of membership within each cluster (in this way the limits are smoothed and it is possible for a specific data to partially belong to more than one cluster). The above are exposed as:

- **Definition 2***:* Let X be the data set and xi an element, such that x_i ∈X.
- **Definition 3:** It is said that a partition $P = \{C_1, C_2, \dots, C_c\}$is a soft partition of data set X, if and only if it is true that: $(\forall x_i \in X, \forall C_j \in P) \leq \mu C_j(x_i) \leq 1$ y $\left(\forall x_i \in X, \exists C_j \in P\right)$ such that $\mu C_j(x_i) > 0$. Where $\mu C_c(x_i) xi$ denotes the degree to which x_i belongs to cluster Cj
- **Definition 4:** A special soft partition is said when the sum of the degrees of membership of a specific point in all clusters is equal to 1 as shown in equation 1.

$$\sum_j \mu C_j(x_i) = 1, (\forall x_i \in X) \tag{1}$$

- **Definition 5:** A constrained soft partition is a partition that meets this additional condition. The Neutrosophic K-Means algorithm produces a constrained smooth partition and to do this the objective function J is extended in two ways:
  - $\forall x_i \in X, \exists C_j \in P$ such that $\mu C_j(x_i) > 0$ where the degrees of neutrosophic membership of each data in each cluster are incorporated or;

- introducing an additional parameter that serves as exponent weight in the membership function, thus the extended objective function *Jm* is as shown in 2.

$$\mu c_1(x_1) = \frac{1}{\sum_{j=1}^{2} \left[\frac{\|x_1 - v_1\|^2}{\|x_1 - v_j\|^2}\right]^2} \tag{2}$$

Where P is a fuzzy partition of the data set X formed by $\{C_1, C_2, \dots, C_k\}$ and the parameter m is a weight that determines the degree to which the partial members of a cluster affect the result.

This refers to a similarity between the classical method and its neutrosophic extension since the latter also tries to find a good partition by searching for the prototypes vi in such a way that they minimize the objective function Jm and that in the same way, it must also look for the functions of membership μC_1that minimize Jm.

In addition to the method, equation 3 is established to calculate the initial membership functions of both clusters:

$$J_m(P, V) = \sum_{j=1}^{k} \sum_{j_k \in X} (\mu c_j(x_k))^m \|x_k - v_j\|^2 \tag{3}$$

The calculations are subsequently updated according to equation 4.

$$v_1 = \frac{\sum_{k=1}^{n} (\mu C_1(x_k))^2 x_k}{\sum_{k=1}^{n} (\mu C_1(x_k))^2} \tag{4}$$

3 Results

The method described above was applied to a dataset that contains information on the earthquakes that occurred in Ecuador in approximately one year. The dataset collects information on the date and time of occurrence, magnitude, latitude, longitude, closest city, area or region, and depth in kilometers. The classical K-means method was combined with the application of neutrosophic techniques to obtain neutrosophic K-means.

For the execution of the methods, the Orange data mining software (Version 3.27.1) was used, which offers many benefits since it allows experimenting with different workflows and applying a wide variety of available widgets until obtaining the desired result. For the application of neutrosophic K-means, the applied workflow was the one shown in the following figure:

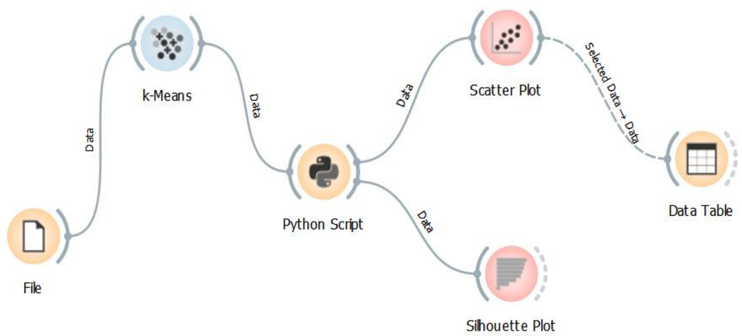


Figure 4. Workflow for Neutrosophic K-means (Orange software).

The dataset is initially loaded through a File widget, then it is processed with the k-Means widget, then Neutrosophy is applied through a Python Script and the results are plotted in a Scatter Plot, as well as a Silhouette Plot, to see in detail the Silhouette values in each cluster. And at the end of the process, a Data Table was placed to better analyze the results: apply filters, count, order, etc.

To define the number of clusters (k), the method offered by Orange's k-Means widget was used, which allows executing several iterations by changing the number of clusters and thus finding the best clustering settings based on the Silhouette Scoring values. The optimal value is the one with the highest Silhouette score, in this case, 0.768, which corresponds to the option of k = 2 clusters.

To include the Neutrosophic part, it was necessary to program a Python script in which formula 3 is applied to calculate the initial membership functions of both clusters, and formula 4 is used to adjust the calculations, iterating the process until the extended objective function is minimized, as expressed in equation 2.

Figure 5 shows the Silhouette plot for the analyzed dataset. As can be seen, two clusters were obtained: one containing 800 and the other 200 data rows where the Silhouette value was calculated based on the Euclidean distance. It can be noted that in cluster 2 (red in figure 5) there is a large amount of data with high Silhouette score values, which indicates that their degree of membership to the cluster in which they are located is remarkably high.

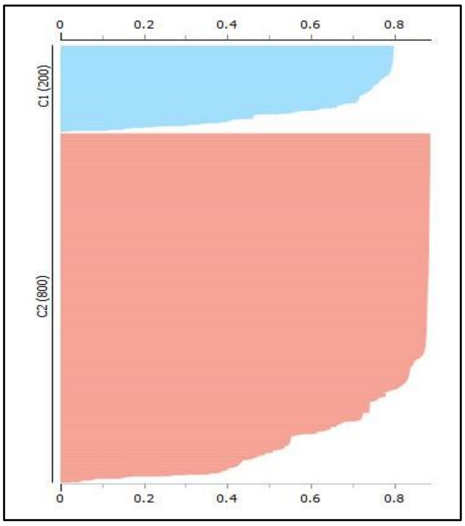


Figure 5. Silhouette Plot based on Euclidean distance.

If we analyze the following image where a graph of Silhouette vs. local time is shown, we can see how the clustering process has segmented the total sample into two sets whose borders are close in the central area of the graph, approximately in August, where we find the group of data with a lower Silhouette value, but the rest of the data is quite well concentrated in their respective clusters. The largest number of points belong to April and May, which indicates that these are probably the dates with the highest level of the propensity for earthquakes.

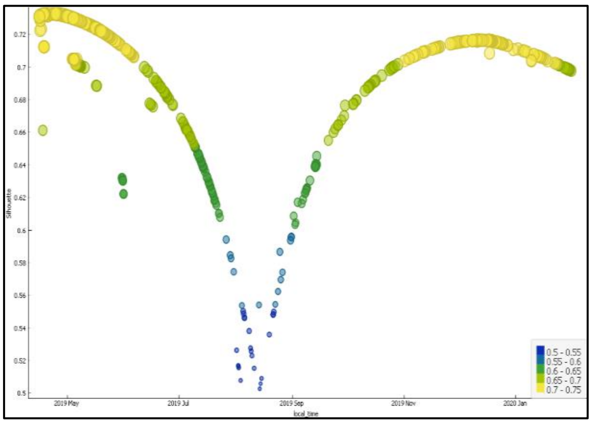


Figure 6. Scatter Plot of Silhouette Scoring vs Local Time.

Another interesting graph we can analyze is the one shown in figure 7, where the y axis displays the magnitudes of the earthquakes, the x-axis shows the local time and the size of the points is defined by the depth (in kilometers). It's harder to find a pattern for the occurrence of the deepest ones, but it is obvious that most of the earthquakes have occurred in the first months of the year, especially in March and April.

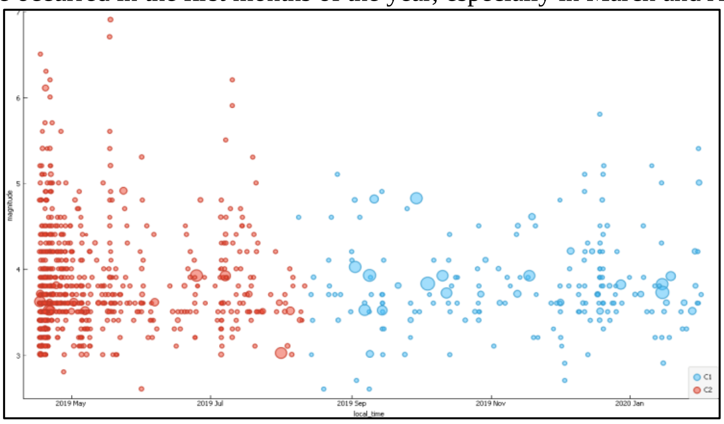


Figure 7. Scatter Plot of magnitude vs local time

Conclusions

In the present work, a data mining analysis was carried out using the K-means neutrosophic clustering method on a dataset with information from earthquakes that occurred in Ecuador, to determine patterns in the data of the sets of clusters obtained to use this information as a possible prediction of future behavior of these phenomena, as well as to take preventive actions and minimize their negative impact.

As a conclusion we can state that the results obtained showed that when applying Neutrosophic K-Means as a Neutrosophic extension of the classical method, it is more advantageous since it can better deal with data that partially belong to more than one cluster; in addition to calculating the prototypes of the cluster, it also calculates the membership functions of the data within each cluster. Neutrosophic K-Means produces a restricted smooth partition of the data set and is therefore useful in situations where the data have characteristics of different groups. This methodology can be applied in many fields such as data classification, medicine, bioinformatics, and economics, among others.

From the processed data, we can conclude that the months most prone to the occurrence of earthquakes are the first months of the year, especially March, April, and May. Therefore, they are denoted as the period of greatest vulnerability. In addition, the highest concentration of earthquakes is located in the first half of the year. In July, August and September, there are not many earthquakes, and if they do occur, they are usually not very intense or are located at a considerable depth.

Based on the data analyzed in the period, it is recommended as a Strategy that government authorities pay special attention to the availability of services in these months with the highest probability of occurrence. Similarly, simulations should be held in schools and places of high concentration of people to achieve greater preparation for emergencies. The season turns out to be of tourist movement so it is important to keep a complete update and preferentially inform the inexperienced and foreign public about the behavior in these situations.

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