Spatial Statistical Analysis of Earthquakes in Kyrgyzstan

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Abstract
The purpose of this study is to apply spatial statistical analysis to earthquake epicenters in Kyrgyzstan and its surrounding areas. Geographical Information System (GIS) has been used for seismic catalog between the years 1900 and 2016 The mean center and directional distribution methods were applied in order to determine where earthquakes compose clusters of different magnitudes. The Average Nearest Neighbor, the Global Moran's Indexand the Getis-Ord General G techniques were used to investigate the spatial pattern analysis of earthquakes. The Anselin Local Moran's Index, and the Getis-Ord Gi techniques were used to examine the spatial distribution of earthquake events in terms of where earthquake hot spot areas are located.*

1. Introduction

Earthquakes regularly occur in the world and are extremely destructive due to their nature, as they occur suddenly and are often accompanied with secondary events (CAERRF, 2015). Earthquakes can cause human injuries and death, huge economic losses by damaging infrastructures, and in very strong cases destroy whole cities. In the last decade, more than 500,000 people died because of earthquakes. Most of these deaths occurred in the continental interiors, where there are several active faults that could cause an earthquake at any time (ODI, 2016).

Kyrgyzstan is a landlocked mountainous country in the eastern part of Central Asia. The country is bordered by Kazakhstan to the north, Uzbekistan to the west, Tajikistan to the south-west and China to the east. The Tien-Shan Mountains cover most of the territory of the country which makes it vulnerable to natural disasters. This mountainous region is vulnerable to destructive earthquakes, even minor magnitude earthquakes are followed by landslides, mudslides, debris flows and floods (UNISDR, 2009). Despite relatively few destructive earthquakes occurred in recent years, the existence of numerous faults means that the region remains a high hazard earthquake zone. According to the Global Seismic Hazard Assessment Program (GSHAP), the Global Seismic Hazard Map shows that Kyrgyzstan is in a region with high to very high seismic hazard areas (Giardini et al., 1999).

Earthquakes are mostly classified based on magnitude - M value. The magnitude as a measure of the energy released by an earthquake is estimated on the basis of the amplitude of seismic waves. The term "magnitude" was first introduced by American seismologist Charles Richter in 1935 to measure the original force, or energy of the seismic events. However, earthquakes with the same magnitude can cause very different damage on the Earth's surface depending on the depth of the hypocenter. In Kyrgyzstan, the hypocenters of strong earthquakes are located in the Earth's crust within depth of 5 to 35 km (Muraliev et al., 2014).

Historically, Kyrgyzstan and adjacent areas have experienced numerous strong earthquakes with magnitudes M>6.0 on Richter scale as Belovodsk in 1885, Vernensk in 1887, Chilik in 1889, Kashgar in 1902, Kemin in 1911, Kemin-Chui in 1938, Chatkal in 1946, Sarykamysh in 1970, Isfara-Batken in 1977, Janalash-Tyup in 1978, Daraut-Kurgan in 1978, Suusamyr in 1992, Kochkor in 2006, Alai in 2008 and other less strong seismic events. The epicenters of strong earthquakes in Kyrgyzstan are concentrated in the North, South, Southwest and Central Tien-Shan Mountains. These catastrophic earthquakes in this region caused huge economic and human losses, and thousands of casualties (Muraliev et al., 2014).

According to the ISDR (2010), the northern Tien-Shan is presently the most seismically active region in Central Asia with earthquakes expected of magnitude M>5.0. Another earthquake prone zone is in the south of Kyrgyzstan near the Fergana Valley and the border with China (Thurman, 2011). These areas contain not only population centers but also industrial and other service areas. The biggest risk in an earthquake is damage caused by buildings collapsing. But the damage can be reduced, if the appropriate building codes are complied with (ODI, 2016). Therefore, it is important to identify and also to map earthquake hot spots in the country. For this reason, GIS based spatial statistical techniques are very useful for describing and modeling spatial data (Scott and Janikas, 2010). It is helpful to understand spatial patterns, distributions, trends and relationships of earthquake events. Many researchers have effectively conducted spatial statistics using the earthquake data in their studies (Al-Ahmadi et al., 2014, Karaburun and Demirci, 2016, Affan et al., 2016). However, the number of earthquake analysis applying GIS based spatial statistics techniques is very limited in Kyrgyzstan. The main task of this study is to conduct spatial statistical analysis of earthquakes in Kyrgyzstan for the time period between 1900 and 2016.

2. Spatial Statistical Analysis

A number of methods are used in spatial statistical analysis and the selected techniques are briefly described below:

a) Mean Center

The mean center identifies the geographic center for a data set of earthquake epicenters. It describes a point constructed from the average X- and Y-coordinate of all the epicenter centroids in the study area. It can be used for tracking changes or for comparing the spatial distributions of different magnitudes of earthquake. The mean center is defined as follow:

$$\bar{X} = \frac{\sum_{i=1}^{n} x_i}{n} \text{ and } \bar{Y} = \frac{\sum_{i=1}^{n} y_i}{n}$$

Equation 1

where x_i and y_i are the coordinates for feature i, and where n is equal to the total number of features (Mitchell, 2005).

b) Directional Distribution

The measuring trend for earthquake magnitudes is necessary to calculate the standard distance separately in the X- and Y-directions. These two calculations define the axes of an ellipse surrounding the distribution of earthquakes. The ellipse is indicated as the standard deviational ellipse, where the X- and Y-coordinates are calculated from the mean center to define the axes of the ellipse. It describes the directional trends of earthquake magnitudes distribution and has a particular orientation. The orientation is defined as the rotation angle of the major axis measured in clockwise direction (Mitchell, 2005). The standard deviational ellipse and the angle of rotation are:

$$SDE_x = \sqrt{\frac{\sum_{i=1}^{n}(x_i - \bar{X})^2}{n}}$$

$$SDE_y = \sqrt{\frac{\sum_{i=1}^{n}(y_i - \bar{Y})^2}{n}}$$

Equation 2

$$tan\theta = \frac{\sqrt{(\frac{(\sum_{i=1}^{n}\tilde{x}_i^2 - \sum_{i=1}^{n}\tilde{y}_i^2) +}{2\sum_{i=1}^{n}\tilde{x}_i\tilde{y}_i}}}{+ (\sum_{i=1}^{n}\tilde{x}_i^2 - \sum_{i=1}^{n}\tilde{y}_i^2)^2 + 4(\sum_{i=1}^{n}\tilde{x}_i\tilde{y}_i)^2)}$$

Equation 3

where x_i and y_i are coordinates from the mean center, θ is a rotation angle, and n is the total number of features.

c) Average Nearest Neighbor

The average nearest neighbor (ANN) computes the distance between each earthquake epicenter centroid and its closest neighboring central location. It then makes averages of all these nearest neighbor distances. In case of spatial distribution analysis of earthquakes is considered clustered, if the average distance is less than the average for a hypothetical random distribution. In inverse case the distribution of earthquakes are considered dispersed if the average distance is greater than a hypothetical random distribution (Mitchell, 2005). The ANN index is expressed as the ratio of the Observed Mean Distance to the Expected Mean Distance:

$$ANN = \frac{\bar{D}_O}{\bar{D}_E}$$

Equation 4

where $\bar{D}_O$ is the observed mean distance between each epicenter and its nearest neighbor:

$$\bar{D}_O = \frac{\sum_{i=1}^{n} d_i}{n}$$

Equation 5

where d_i is the distance between earthquake epicenter i and the nearest neighbor, n is the total number of earthquakes. The expected distance $\overline{D}_E$ is the average distance between neighbors in a hypothetical random distribution:

$$\overline{D}_E = \frac{0.5}{\sqrt{n/A}}$$

Equation 6

where A is the total area of research interest. The ANN calculates a Nearest Neighbor Index (NNI), Z-score and P-value based on the average distance from each earthquake to its nearest neighboring earthquake epicenter. If NNI is less than 1, the pattern indicates clustering. If NNI is greater than 1, the pattern shows a tendency toward dispersion. Z-scores are standard deviations and the P-value is a probability. If a Z-score is less than -1.96 or greater than +1.96 in the analysis, the pattern shows significant clustering. In this case the P-value is less than 0.05 that associated with a 95 percent confidence level. If a Z-score is between -1.96 and +1.96, the pattern indicates a random distribution (Mitchell, 2005, Al-Ahmadi et al., 2014).

d) Global Moran's Index

The Global Moran's Index (GMI) measures spatial autocorrelation based on both epicenter locations and attribute values of seismic events. The GMI indicates the level of spatial concentration or dispersion for a specific point pattern (Scot and Janikas, 2010). It calculates whether the spatial pattern of earthquakes is clustered, dispersed, or random. Both a Z-score and P-value evaluate the significance of the GMI value. When one of the Z-score or P-value indicates statistical significance, a positive GMI value exhibits tendency toward clustering, while a negative GMI value exhibits toward dispersion (Mitchell, 2005). The Moran's statistic for spatial autocorrelation is given as follow:

$$\mathrm{GMI} = \frac{n}{S_O} \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{i,j} z_i z_j}{\sum_{i=1}^{n} z_i^2}$$

Equation 7

where z_i is the deviation of an attribute for epicenter i from the average $(x_i - \overline{X})$, $w_{i,j}$ is the spatial weight between epicenter i and j, n is equal to the total number of earthquakes, and S_O is the aggregate of all the spatial weights. The calculated GMI value ranges between -1and +1. The spatial autocorrelation is positive (correlation) when the GMI value is between 0 and +1. Meanwhile, if the spatial autocorrelation is negative (no correlation), the GMI value is between 0 and -1 (Mitchell, 2005). The GMI statistic is a single indicator used to investigate the spatial autocorrelation and patterns of the earthquakes in the study area.

e) Getis-Ord General G

The Getis-Ord General G (GOGG) was introduced by Getis and Ord as global statistics to analyze the spatial patterns (Getis and Ord, 1992). The GOGG measures the degree of clustering for either high values (hot spots) or low values (cold spots). If Z-score value is positive, the GOGG observed index value is larger than the expected index, it indicates that high values are clustered. If Z-score value is negative, the GOGG observed index value is smaller than the expected index value, indicating low values for the attribute of earthquakes that are clustered in the study area. The GOGG is calculated by the following formula:

$$\mathrm{GOGG} = \frac{\sum_{i=1}^{n} \sum_{j=1}^{n} w_{i,j} x_i x_j}{\sum_{i=1}^{n} \sum_{j=1}^{n} x_i x_j}, \forall j \neq i$$

Equation 8

where x_i and x_j are attribute values for epicenters i and j, and $w_{i,j}$ are the spatial weights for these two earthquakes (Mitchell, 2005).

f) Anselin Local Moran's Index

The Anselin Local Moran's Index (ALMI) was suggested by Anselin (1995). It identifies local clusters and spatial outliers of earthquake magnitudes which can be calculated by the following equation:

$$I_i = \frac{x_i - \overline{X}}{S_i^2} \sum_{j=1, j\neq i}^{n} w_{i,j} (x_j - \overline{X})$$

Equation 9

where x_i is an attribute for epicenter i, $\overline{X}$ is the mean of the related attribute, and $w_{i,j}$ is the spatial weight between earthquake epicenters i and j. The ALMI identifies spatial clusters of earthquake magnitudes with high or low values. A positive value for the ALMI means that an epicenter has neighboring epicenters with similarly high or low attribute values, which considers of spatial clusters. The value of clusters consists of the higher value (High-High) and lower value (Low-Low). A negative value for the ALMI means that an epicenter has neighboring epicenters with dissimilar values, where this epicenter is a spatial outlier. If an earthquake epicenter with a high value is surrounded by a low value it is High-Low and if an epicenter with a low value is surrounded by epicenters with high values it is Low-High (Mitchell, 2005). In positive and negative value cases, the P-values should be small (P<0.5) for the spatial cluster or spatial outlier in order to be considered statistically significant (Anselin, 1995, Al-Ahmadi et al., 2014).

*g) Getis-Ord Gi**

The Getis-Ord Gi* (GOG) identifies statistically significant hot spots and cold spots within the context of neighboring earthquake epicenters (Getis and Ord, 1992). Hot spot means statistically significant clusters of high magnitude values and it is surrounded by other high values of the seismic event. Cold spot means statistically significant clusters of low magnitude values and it is surrounded by other low values of the event. The calculation of the Getis-Ord GI* is defined by the following equation (Mitchell, 2005):

$$G_i^* = \frac{\sum_{i=1}^{n} w_{i,j} x_j - \bar{X} \sum_{i=1}^{n} w_{i,j}}{S \sqrt{\frac{\left[n \sum_{j=1}^{n} w_{i,j}^2 - \left(\sum_{j=1}^{n} w_{i,j}\right)^2\right]}{n-1}}}$$

Equation 10

where x_j is an attribute value for epicenter j, $w_{i,j}$ are the spatial weight for epicenters i and j, and n is the number of earthquakes.

The GOG statistic uses a neighborhood based either on a set distance or on adjacent earthquake epicenters. This statistic returns a Z-score, P-value and confidence level bin Gi_Bin-value for each event in the dataset. For statistically significant positive Z-score values, the higher the value of the Z-score and small P-value, the more intense the clustering of high values (hot spot) is. For statistically significant negative Z-score values, the smaller the value of the Z-score, the more intense the clustering of low values (cold spot) is. A Z-score value near zero indicates no apparent spatial clustering. It happens when the surrounding values are close to the mean, or when the target epicenter is surrounded by the mix of high and low values (Mitchell, 2005; Al-Ahmadi et al., 2014). Gi-Bin values in the +/-3 reflect statistical significance with a 99 percent confidence level, (Mitchell, 2005).

3. Study Area and Earthquake Data

Kyrgyzstan occupies a large part of the Tien-Shan and northern areas of the Pamir mountains and is one earthquake-prone region (Figure 1). The North Tien-Shan and South Tien-Shan are seismically active zones that are located exactly at the north and south border areas of the country (CAERRF, 2015).

The total seismic energy in the North and South Tien-Shan Zones is 20 times higher than in other seismically active areas (Muraliev A., et al 2014). The present earthquake catalog of Kyrgyzstan was collected and generalized for more than 100 years. At different times this work was carried out by the research staff members of several institutions. The first systematic non-instrumental observations of earthquakes in Central Asia including the territories of Kyrgyz Republic were initiated by the Russian Geographical Society.

Figure 1: Study area, Kyrgyzstan

They compiled and published a catalog of earthquakes from ancient periods to 1887. The next observation results of sensible and strong earthquakes up to 1936 in the territory of the USSR, including Kyrgyz Republic, were collected and summarized by the Seismological Institute, Academy of Sciences, USSR. Since the establishment of the first seismic station in the territory of Kyrgyz Republic in 1927, where the main work on the generalization of instrumental observations of earthquakes in Central Asia was completed in 1956. Further instrumental records of earthquakes in Kyrgyz Republic were conducted by the newly established Institute of Seismology at the Academy of Sciences of the Kyrgyz Republic (Kalmetova et al., 2009).

After the independence of Kyrgyzstan, it is renamed as the Institute of Seismology at the National Academy of Science of Kyrgyzstan. This institution has a network of seismic stations throughout the country that allows monitoring earthquake activity and actively cooperates with neighboring and other foreign countries (CAERRF, 2015). The regional network of analogous seismic stations were continuously recording local earthquakes with magnitude M≥3.0 or energy class K≥9.0 during the periods of 1955-2008 years. In 2009 and 2010, the analogous seismic stations were replaced by digital ones (Muraliev et al., 2014). For our research study, the earthquake catalog covering the coordinates 39°0′ - 44°0′ of the northern latitude and 69°0′ - 81°0′ of the eastern longitude was provided by the Institute of Seismology, Kyrgyzstan. This institution uses different magnitude scales: M_L - local magnitude; M_b-body wave magnitude; M_s-surface wave magnitude; and M_w -moment magnitude.

The national earthquake catalog with M≥3.0 for the time period 1900-2016 was selected and used for spatial statistical analysis. 15866 earthquakes occurred in our study area and the descriptive dataset statistics can be seen in Table 1.

Most of these earthquakes (72.7%) have small magnitude 3≤M<4 on the Richter scale. Magnitude 4≤M<5 earthquakes are registered in 23.1% of cases. 584 earthquakes had a magnitude of 5≤M<6, while only 87 strong earthquakes with magnitude of M≥6 on the Richter scale have been experienced in the study area.

4. Results and Discussions

The earthquake data is converted into a geodatabase of ArcGIS software by the ESRI. The WGS 1984 geographic coordinate system is used. This data characterized by the following attributes: longitude, latitude, year, month, day, hour, minute, second, magnitude, energy class and depth. The spatial distribution of earthquakes with different magnitudes on the Richter scale is shown in Figure 2. The central tendency and directional distribution method was applied to the earthquake data. First, we examined the distribution of mean centers of earthquakes, which identified the geographic center for each category of earthquake magnitudes. It was useful for comparing the distributions of different types of magnitudes. Directional distribution method created a standard deviational ellipsis in order to determine the spatial characteristics and display directional trends of earthquake magnitudes in the study area. A one standard deviation was applied for the standard deviational ellipse size.

The calculated parameters of the mean centers and the standard deviational ellipses are given in Table 2. Based on this table, we can see that the X-coordinate of the mean center slightly changed as earthquake magnitude increased. The biggest length of both major and minor axes of the standard deviational ellipses is found for magnitude 5≤M<6, while the shortest is found for magnitude 4≤M<5. The location of the mean centers as point feature and the standard deviational ellipses for each category of magnitudes are shown in Figure 3. The mean centers are represented with different symbols and each of them is associated to a deviational ellipse of the same colors.

Table 1: Statistics of earthquakes that occurred between 1900 and 2016

Magnitude	Earthquake Total	Earthquake %	Magnitude			
			Minimum	Maximum	Mean	SD
3≤M<4	11537	72.7 %	3	3.9	3.471	0.279
4≤M<5	3658	23.1 %	4	4.9	4.309	0.252
5≤M<6	584	3.7 %	5	5.9	5.266	0.257
M≥6	87	0.5 %	6	8.2	6.451	0.437
3≤M≤8.1 (all)	15866	100 %	3	8.2	3.750	0.575

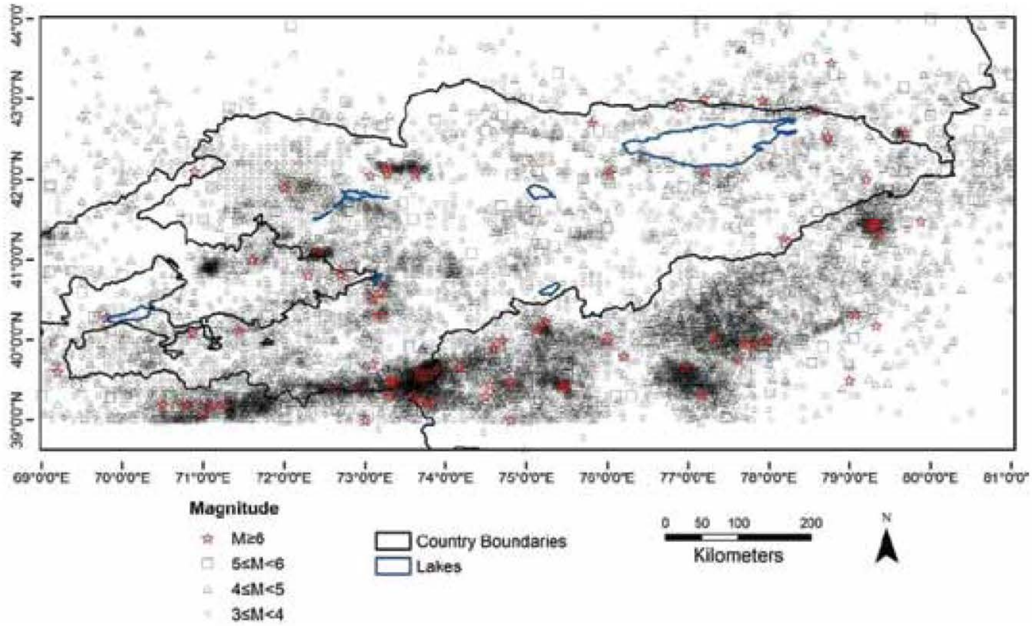

Figure 2: Earthquake distribution for the time period 1900-2016

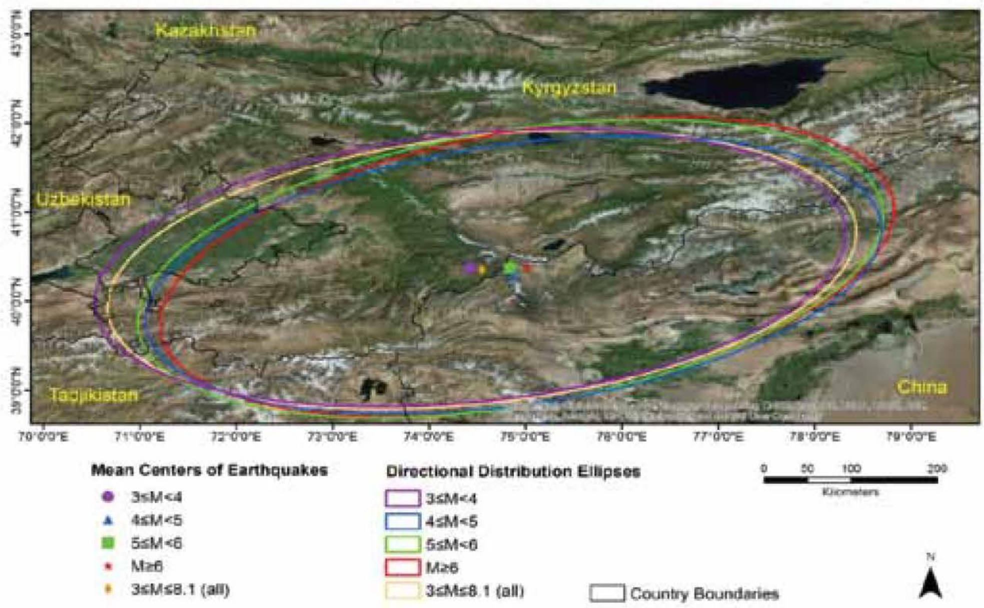

Figure 3: Distribution of the mean centers and the standard deviational ellipses

Table 2: Parameters of mean centers and directional deviation ellipses

Magnitude M	**Mean Center**		**Standard Deviation Ellipse**		
	X	Y	Major Axis (km)	Minor Axis (km)	Rotation (degree)
3≤M<4	74.42	40.37	783	300	83.4
4≤M<5	74.88	40.30	771	291	81.1
5≤M<6	74.84	40.37	784	308	79.5
M≥6	75.02	40.39	773	305	78.6
3≤M≤8.2 (all)	74.55	40.36	782	299	82.8

The spatial distributions of the mean centers of earthquake magnitudes are concentrated in the areas of the Central Tien-Shan Mountains, especially near the boundaries of Kyrgyzstan and China. As seen from Figure 3, where the mean centers of three categories of earthquake magnitude 3≤M<4, 5≤M<6 and 3≤M≤8.1 (all) are located in the territory of Kyrgyzstan, while other two categories 4≤M<5, M≥6 are displayed in the territory of China. This map shows that mean centers of earthquake magnitudes shifts from west to east. And each ellipse shows the distributional trend of earthquakes by magnitude. Global spatial statistics techniques of Average Nearest Neighbor (ANN), Global Moran's Index (GMI) and Getis-Ord general G (GOGG) were applied to the earthquake data. These techniques were applied to each of the four categories of magnitudes and to the whole data which contains all magnitudes of earthquakes. The calculation results are shown in Tables 3, 4 and 5.

According to the Table 3, where Index and Z-score values for each magnitude categories are less than 1. It indicates that patterns of earthquakes in the study area are spatially clustered. The only ANN method showed that the spatial patterns of each category of magnitude are clustered. This method does not consider earthquake magnitude in its analysis and the Euclidean distance method is used in calculation process. Both the GMI and the GOGG methods consider values of earthquake magnitudes, where the inverse distance method for conceptualization of spatial relationships in dataset and the Euclidean distance method for distance calculations were used.

The results of GMI in Table 4 are showing the clustered pattern in all categories, except in the largest event with magnitude M≥6, where it indicates spatial random data. Here we can see that Index and Z-score values are negative and the P-value is statistically significant. In this case the spatial distribution of high values and low values in the earthquake dataset is more spatially dispersed that indicated as random. The other earthquake data is spatially clustered such as the Index and Z-score values are positive and the P-value is statistically significant. The results of GOGG in Table 5 showed high clustering for earthquake with magnitude 4≤M<5 and low clustering for the whole earthquake data 3≤M≤8.1 (all). In these cases the highest Z-scores value shows higher intensity of clustering and the lowest Z-scores value shows the lower clustering. The other three categories of magnitude indicate that the spatial random patterns within the study area. The ANN, GMI, and GOGG are global statistics. These methods provided a summary of the pattern of earthquakes over the whole study area.

Table 3: Average nearest neighbor

Magnitude (M)	Index	Z-score	P-value	Pattern type
3≤M<4	0.584812	-85.314321	0.000000	Clustered
4≤M<5	0.647914	-40.738133	0.000000	Clustered
5≤M<6	0.692505	-14.215936	0.000000	Clustered
M≥6	0.771613	-4.075314	0.000046	Clustered
3≤M≤8.2 (all)	0.571934	-103.151432	0.000000	Clustered

Table 4: Global Moran's index

Magnitude (M)	Index	Z-score	P-value	Pattern type
3≤M<4	0.07907	10.352712	0.000000	Clustered
4≤M<5	0.152164	4.347528	0.000014	Clustered
5≤M<6	0.549179	4.103414	0.000041	Clustered
M≥6	-0.247238	-1.247875	0.212077	Random
3≤M≤8.2 (all)	0.172547	26.846153	0.000000	Clustered

Table 5: Getis-Ord general G

Magnitude (M)	Index	Z-score	P-value	Pattern type
3≤M<4	0.000253	-0.529391	0.596534	Random
4≤M<5	0.000120	3.474138	0.000512	High-Clusters
5≤M<6	0.000323	0.634058	0.526043	Random
M≥6	0.006263	-0.564834	0.572187	Random
3≤M≤8.2 (all)	0.000180	-6.744111	0.000000	Low-Clusters

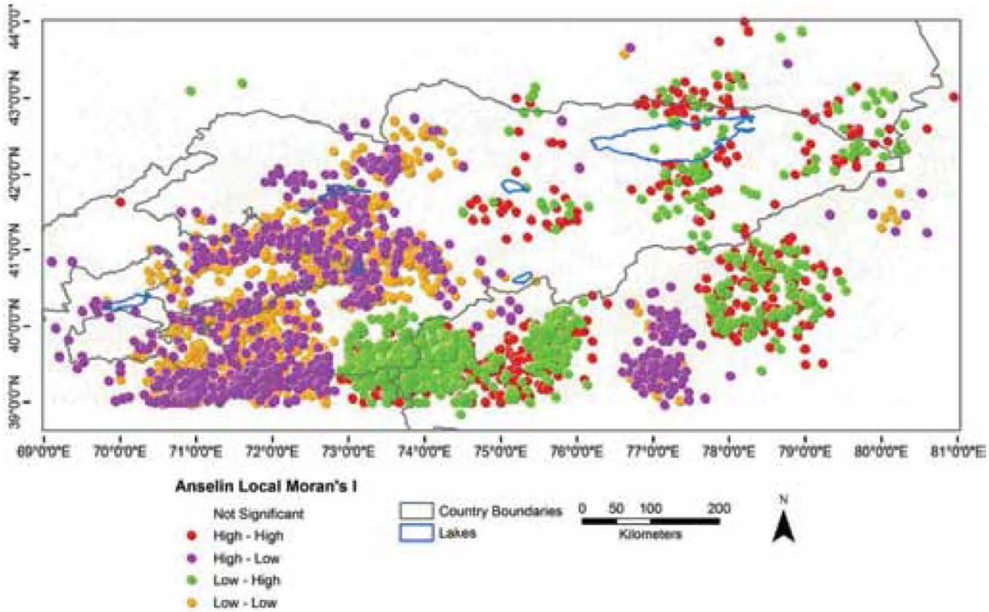

Figure 4: Cluster analysis using the Anselin local Moran's index method

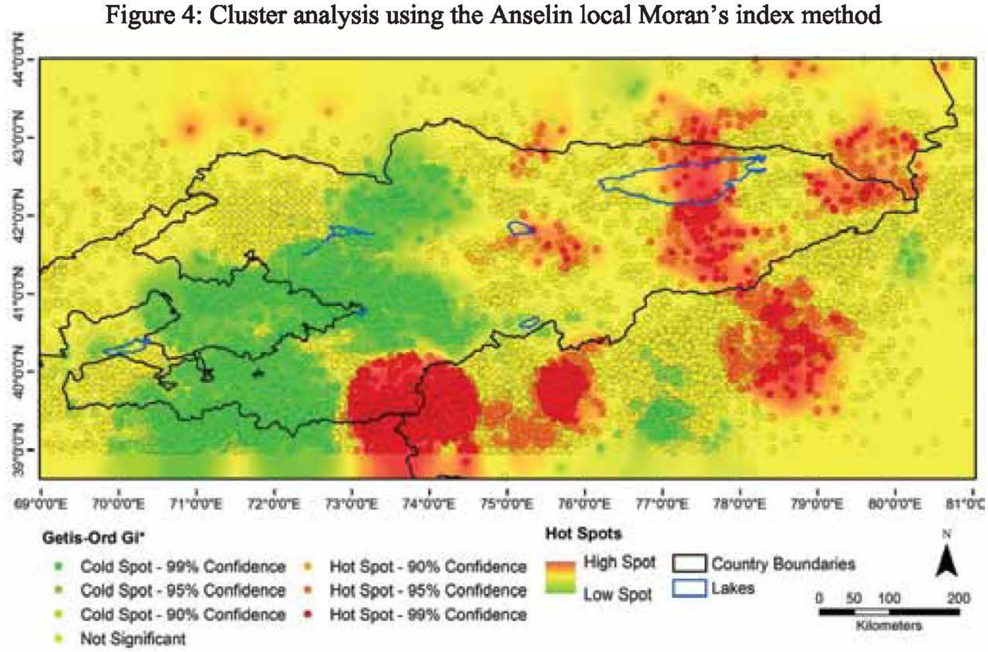

Figure 5: Earthquake hot spot analysis using Getis-Ord-Gi* method

The next Anselin Local Moran's Index (ALMI) and Getis-Ord-Gi* (GOG) are local statistics. These methods were applied to earthquake dataset to identify the presence of spatial clusters and hot spots across the study area. They used the whole earthquake dataset in the application processes of both the ALMI and the GOG methods, where the fixed distance band method and 67 kilometer threshold distance value was used for conceptualization of spatial relationships.

This threshold distance value was determined by GMI calculations. Figure 4 shows the results of the Anselin Local Moran's Index analysis, which included the whole earthquake data $3 \leq M \leq 8.1$ (all). In this figure, spatial clusters of earthquake magnitudes are shown by red, violet, green and orange dots. Here grey dots are not significant spatial clusters. The red dots represent earthquakes with high magnitudes, which are surrounded by high earthquake magnitudes.

In contrast, the orange dots represent low magnitude surrounded by other low magnitude earthquakes. The violet and green dots represent the presence of spatial outliers, where high magnitude earthquakes surrounded by low magnitudes and low magnitudes surrounded by high magnitude earthquakes, respectively.

Spatial clusters of earthquakes are clearly highlighted in specific areas across the study area. Here, we can categorize the occurrence of earthquakes with high magnitudes into five clusters. The two large high clusters are mostly located in the territory of China, the first one in the South Tien-Shan (between 73 ° E and 76° E) and the second one in the Southeast Tien-Shan (between 77°30′ E and 79°40′ E); the next high cluster in the Northeast Tien-Shan (between 79 ° E and 81° E); another one is in the North Tien-Shan, especially in southern and northern parts of the well-known Issyk-Kul Lake (between 41° N and 43° N); and the last high cluster going from the middle of the territory to the northern boundary of Kyrgyzstan. There are also clusters of low magnitude earthquakes, which range from the southwest border to the north of the country.

The results of the earthquake hot spot analysis using the Getis-Ord-Gi* method are presented in Figure 5. In this figure, the statistical results of earthquake hot spot analysis and continuous hot spot surface are represented at the same time. The green dots are statistically significant cold spots, where low magnitude earthquakes are surrounded by other low magnitude earthquakes. The red dots are statistically significant hot spots, where high magnitude earthquakes are surrounded by other high magnitude earthquakes. The beige dots are not part of statistically significant clusters. The continuous Distance Weighting (IDW) technique, where GiZ-Score value of hot spots was interpolated.

The areas of low spots in green are continuously changing to areas of high hot spots in red. These areas in red can be regarded as high seismic zones. The big earthquake hot spot areas are highlighted within ranges of the North and the Southeast Tien-Shan mountains passing through the Issyk-Kul Lake. The next hot spot areas appear in the South Tien-Shan, especially in trans-boundary countries of Kyrgyzstan, China and Tajikistan. Comparison with the results of the Anselin Local Moran's Index (ALMI) and the Getis-Ord-Gi* methods, the ALMI provided more local details about the spatial clusters. For instance, the Getis-Ord-Gi* method indicated the South Tien-Shan areas as hot spot areas, while the ALMI method showed the spatial disaggregation into high-high and low-high magnitude clusters of earthquakes.

5. Conclusions

The purpose of this study was to perform the Geographical Information System (GIS) based spatial statistical analysis of the earthquake epicenters in Kyrgyzstan and its surrounding areas in a time period between 1900 and 2016. As seen from the used earthquake catalog, the territory of Kyrgyzstan is high earthquake prone zones. Most of the territory of the country is covered by Tien-Shan Mountains, where the occurrence of any earthquake can directly trigger or accelerate other natural hazards, including landslides, mudflows, rockslides, and soil liquefactions. Therefore, it was important to analyze the earthquake spatial distribution and spatial statistics to identify seismic active areas.

Different spatial statistical techniques were applied to the earthquake data. First, the central tendency and directional distribution method was applied to the earthquake data. Mapping the location of the mean centers and the distributional trend for different magnitudes over study area might indicate how the earthquakes are spatially distributed. The study showed that the mean centers of earthquakes are concentrated in the areas of the Central Tien-Shan Mountains, especially near to boundaries of Kyrgyzstan and China. Comparing the shape and overlap of ellipses with the locations of urban areas can be useful in deploying mitigation of damage strategies.

The global spatial statistics techniques of the Average Nearest Neighbor, the Global Moran's Index and the Getis-Ord general G were applied to different magnitudes and also to the whole data of earthquakes in the study area. These methods relied on a set of basic assumptions, which provided a summary of the pattern of earthquakes over the whole study area. The local spatial statistics techniques of the Anselin Local Moran's Index and Getis-Ord-Gi*were applied to earthquake dataset to identify the spatial distribution of earthquake hot spots across the study area. The Anselin Local Moran's Index method determined the spatial clusters of earthquakes with high magnitudes, which are distributed in the South, Southeast, North and Northeast Tien-Shan. The spatial clusters of low magnitude earthquakes were identified in an area which ranged from southwest to north in the study area.

The Getis-Ord-Gi* method represented the distribution of earthquake hot spots that appeared in the North, Southeast Tien-Shan and South Tien-Shan, especially high spot in trans-boundary countries of Kyrgyzstan, China and Tajikistan. This method provided the spatial distribution of events in terms of where earthquake hot spots and high seismic areas are located. Based on this study, we can conclude that most of the territory of Kyrgyzstan lies in high earthquake prone areas. Therefore, it is necessary to take precautions in order to reduce the loss of human life and property from possible earthquake in the future.

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