Pattern analysis of seismicity around Mavrovo lake: a case study for the period July 2020 - November 2021

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ABSTRACT: Two moderate earthquakes with magnitude M_L5.0 happened on 11th of November 2020 near the Mavrovo lake in northwestern Macedonia. Mavrovo lake is an artificial reservoir with a dam built between 1947 and filled by 1953. Its maximum length is 10 km, width is 5 km and the depth is 50 m. We try to investigate the common factors which might be causing earthquakes, for example local geology and seismotectonic regime in the region.

Seismic events of such size can have various sequences of foreshocks and aftershocks, which mostly depend on the earthquake mechanism. In this case study a numerical analysis was done for the first time from the list of events reported by the Skopje Seismological observatory, that occurred some six months prior to the main events and one year after, till November 2021.

A list of over 100 earthquakes registered by the local and regional stations with magnitudes equal or greater than M_L1.7 was analyzed in more details in terms of temporal and spatial distribution around the lake, in a polygon area defined by geological features. No statistically significant clustering of events was noticed in the foreshock period from July 2020. In the aftershock period, the most numerous events lasted about a month after the main events. However, there was another period of increased seismicity during March 2021, followed by gradual decrease onwards.

The preliminary distribution of epicenters was mainly along the terrain of Radika river and close monitoring continues to establish possible longer-term variations of seismicity. Comparative analysis with various periods will be also considered in order to determine any patterns of seismicity.

Keywords: Earthquake, epicentral map, regional seismicity.

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INTRODUCTION

Mavrovo Lake is an artificial reservoir in the northwestern part of Macedonia. It is located in Mavrovo national park at 1,200 m above sea level, between forested and high mountains Bistra, Korab and Shar (Fig.1).

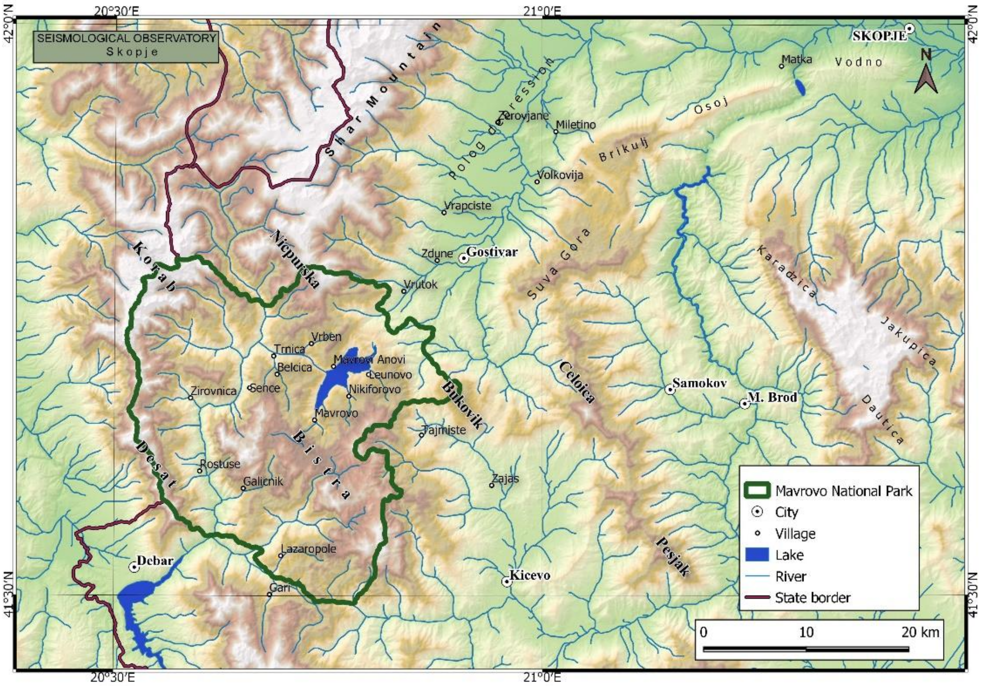


Figure 1: Location map of Mavrovo national park.

Until 1947, on the place of today's lake was the Mavrovo Valley, with grassy pastures and fields of wheat, rye, oats and barley (prof. Gjorgji Sinadinovski, personal communications, 2021). Three rivers named after villages of Leunovo, Nikiforovo and Mavrovo had flowed through the valley into the Mavrovo River, which was closed with a big earthen dam at its original confluence to river Radika (Fig. 2). The valley began to fill with water and over the course of a few years the Mavrovo Lake was formed.

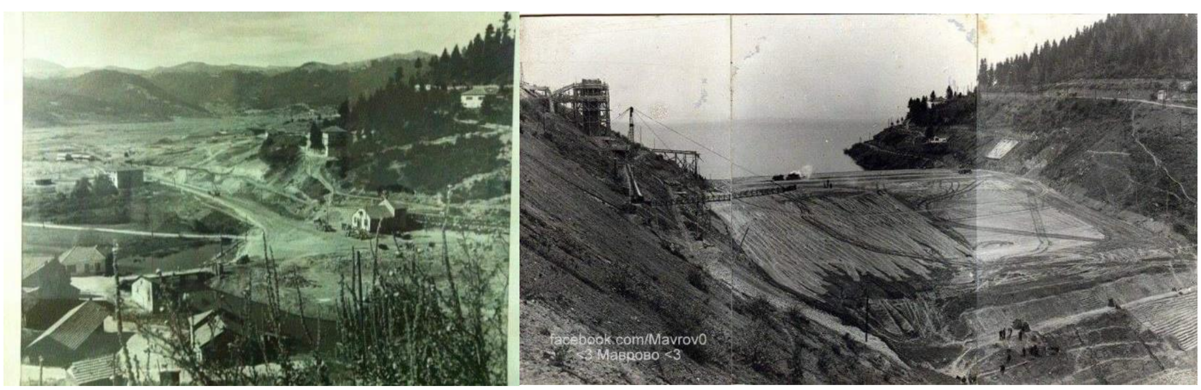


Figure 2: Beginning of the construction of the dam at Mavrovo Lake, cc. 1950 (archive picture).

By 1953, the newly created lake flooded 1,370 hectares of land of the then Mavrovo Field, collecting about 357 million cubic meters of water, mostly over meadows and pastures. To date, Mavrovo Lake is 10 km long and 5 km wide. It reaches the greatest depth of 50 m near the dam which is 54 m high, 210 m long and 5 m wide. The lake is filled not only with smaller tributaries, but also with water from the river Radika on the northern side. The canaled water of that river is used for obtaining electricity and for irrigation.

REGIONAL SEISMOTECTONICS

The Earth's crust on the Balkan Peninsula is highly heterogeneous due to former plate motions and continental collisions. Subduction of the African under the Eurasian plate is located in the Hellenic subduction zone and the dominant type of neotectonic movement is extension (Arsovski, 1996). It explains the existence of the complicated extensional-compression zones appearing on terrain in irregular ways.

The territory of Macedonia is a part of the Balkan Peninsula in the Mediterranean seismic belt. It is a complex geological, tectonic and seismotectonic area of active intra-plate tectonics and high seismicity. Its seismicity is associated with recent tectonic movements along normal faults. The normal fault tectonics is a consequence of extensional processes that started at the end of the Early Miocene, which affected the larger part of the Balkan region and still is present today (Dumurdzanov et al., 2020).

During the Middle Miocene a period of extension and evolution of neotectonic movements took place on the territory as well. Intense vertical movements resulted in the development of numerous morphostructures of uplift (horsts) and subsidence (grabens). The process of differentiation displacements between depressions and horst massifs was intensified with time, resulting in the activation along faults, which represent natural borderlines between these morphostructural units (Arsovski, 1996, Jancevski, 1987, and Iliovski et al., 2003).

The study area, Mavrovo region, is located at the northwestern part of Macedonia (Fig.3). It exhibits a large variety of morphological expressions associated with the seismic activity of the region. Figure 3 displays the spatial distribution of the 1970-2021 earthquakes as circles in respect to their size i.e. magnitude, over the region with the major lakes and rivers drawn in blue and the known geological features (faults system, as red lines). The distribution of epicenters is mainly along the Radika river and a few smaller tributaries to the lake system.

This region belongs mainly to the Tetovo-Gostivar epicentral zone, historically characterized with occasional occurrence of moderate to strong earthquakes with magnitudes $M \geq 5$ and frequent weak earthquakes. Very small part of the Mavrovo region belongs to Kicevo epicentral zone, which is characterized by moderate to weak earthquakes with magnitude $M \leq 5.0$.

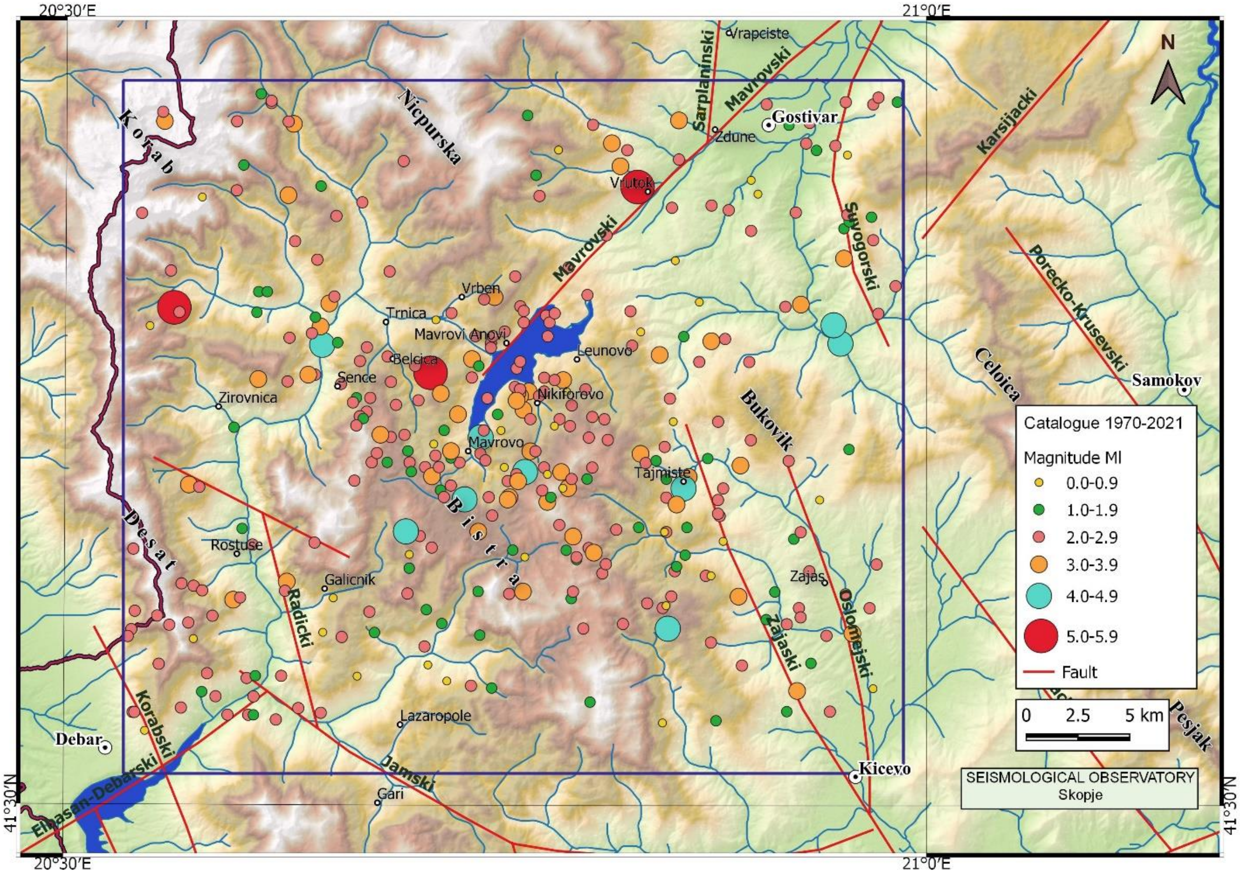


Figure 3: Seismotectonic map of the study region with earthquakes in period of 1970-2021.

The earthquakes that occur in this zone result from recent tectonic processes, first of all, the existence of recent Neogene-Quaternary small depressions Polog and Kicevo valleys from one side and Bistra, Korab and Shar grabens on the other hand. The process of differentiation displacements between depressions and horst massifs resulted in the activation of margin faults, which represent natural borderlines between these morphostructures.

The differential motions can still cause accumulation of energy that might produce earthquakes with magnitudes of up to M=5.0. The seismicity of Mavrovo region is related to the activation of neotectonic Mavrovo fault, which belongs to the seismically active Skopsko-Kustendil fault and the north part of the Zajas fault. In that part we have complex area, where a tectonic knot exists (Arsovski and Hadzievski, 1970), between Mavrovo and Bistra faults, which hasn’t express high seismicity yet.

SEISMICITY IN 2020-2021 PERIOD

During the period November 2020 to March 2021 an increased seismic activity was recorded by the Macedonian telemetric seismological network and neighboring countries (Chernih et al., 2021 and Drogreshka et al. 2021), culminating in two moderate earthquakes with magnitude M_L5.0 which happened on 11th of November 2020. The isoseismal map of the second earthquake is presented on Figure 4.

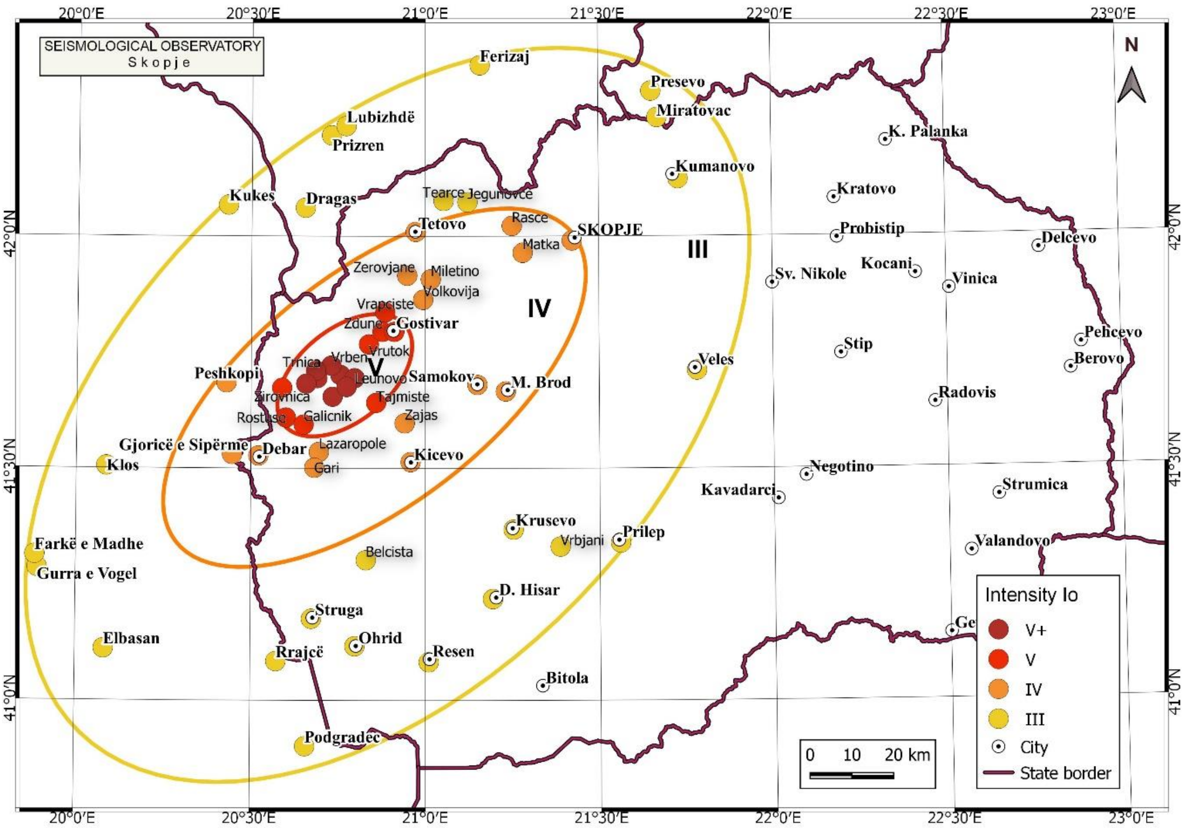


Figure 4: Isoseismal map of the second earthquake on 11th of November 2020.

This study was performed with an updated catalogue of earthquakes registered by the local stations with magnitudes $M_L \geq 1.7$ and for period of 6 months prior and 11 after the strongest events. For the 50x45 km rectangle centered over the Mavrovo Lake, more than 100 earthquakes registered by the local stations were selected and processed with HS6.2 program (Herak et al., 2021).

The list of the strongest earthquakes with magnitudes $M_L \geq 3.5$ and their maximum felt intensity I_0 (EMS-98 scale) in the investigated period between July 2020-November 2021 is shown in Tab. 1. No specific time clustering of events was noticed in the foreshock period from July 2020 (Fig.5). In the aftershock period, the most numerous events lasted about a month after the two strongest events occurred. However, there was another period of increased seismicity during March 2021, followed by gradual decrease onwards.

Table 1: The strongest earthquakes in the region of Mavrovo Lake (after Chernih et al., 2021).

Year	**Month**	**Day**	**h:min:s**	φ	λ	**h(km)**	M_L	I_o
2020	11	11	03:54:14.73	41.61	20.85	15.0	5.0	V-VI
2020	11	11	05:23:46.13	41.67	20.74	15.8	3.5	III
2020	11	11	12:26:36.74	41.64	20.80	14.5	3.8	III
2020	11	11	14:25:12.97	41.59	20.87	11.8	5.0	V-VI
2020	11	11	15:43:22.23	41.58	20.76	20.9	3.8	III
2021	1	27	00:36:46.42	41.72	20.71	15.0	3.5	IV
2021	1	27	06:44:07.93	41.68	20.76	15.8	3.7	IV
2021	3	12	21:17:07.75	41.66	20.74	17.2	4.6	V
2021	3	12	21:28:40.64	41.63	20.73	15.0	4.4	IV-V
2021	3	14	21:38:55.90	41.64	20.73	17.5	3.9	III

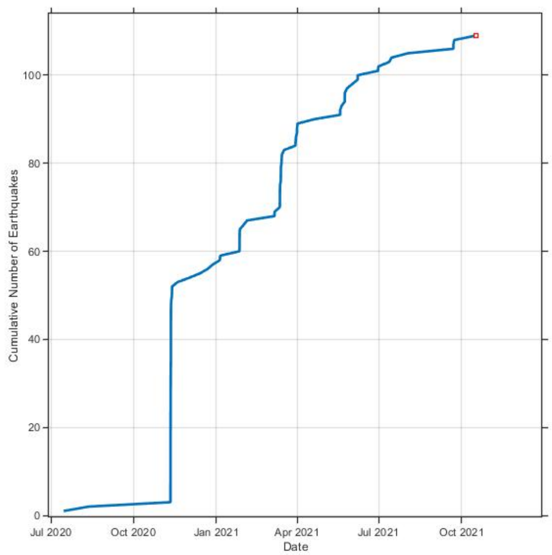


Figure 5: Cumulative number of earthquakes in the study region (Jul 2020 – Nov 2021).

SEISMIC ANALYSIS

Bulletins by the Seismological Observatory of the Republic of North Macedonia (SORM) for earthquakes reported in the period of 1970-2021 were used for the study area.

Our area of interest was defined according to the regional seismotectonics (Fig. 3), in the polygon (41.55-41.85 °N, 20.525-20.90 °E). A catalogue of earthquake data was prepared to apply the Gutenberg-Richter relation (1) between the number of earthquakes (N) and their magnitudes (M),

$$LogN = a - bM \tag{1}$$

to obtain the values of the coefficients a and b.

The catalogue provided does not have magnitude scale variations due to the usage of uniform scale. Additionally, the original scale was converted into the moment magnitude scale M_w (Stejskal, Pekevski et al. 2010).

$$M_w = 0.9203 * M_L + 0.3987 \tag{2}$$

The most significant issue that may affect the values of a and b was detected to be the magnitude of completeness (M_C), because of the insufficient number of stations and their detectability in selected areas (Sinadinovski and M^{c}Cue, 2001). In our case, the limited data availability results in selection of only 354 earthquakes.

M_C was determined using the maximum value of the first derivative of the frequency-magnitude curve and a value of 2.5 was assigned. The dataset was processed by the method included in the ZMAP software (Wiemer, 2001). The values of coefficients a and b calculated using ZMAP software were further verified by in-house calculated values using the least-square method. A grid of 0.05^ox0.05^o squares were assigned for coefficients' calculation.

The frequency-magnitude occurrence relationship helps to characterize the activity in a given polygon. The magnitude, spatial distribution of epicentres and the occurrence in time can be used to model the temporal and spatial randomness. The rate of recurrence of earthquakes on a seismic source is assumed to follow the Gutenberg-Richter relation given in equation (1).

The distribution of values for a and b for the discretised polygon is shown on Figure 6. The calculation shows that the Mavrovo polygon is characterized by a higher value of a and b in the northern part of the dominant fault structure.

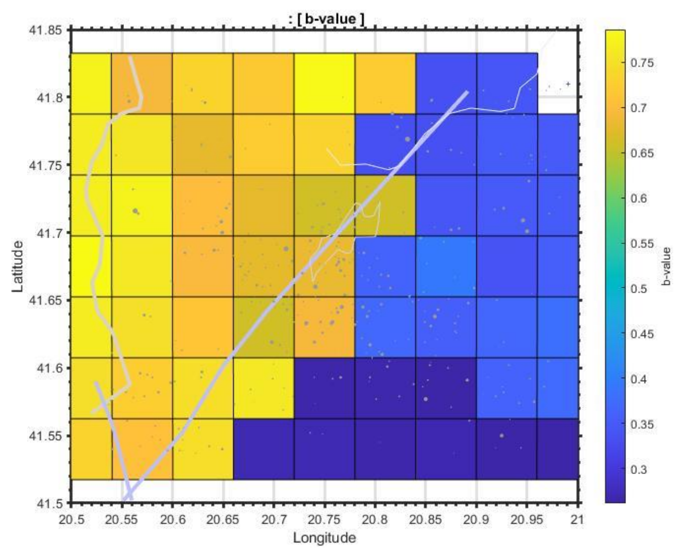
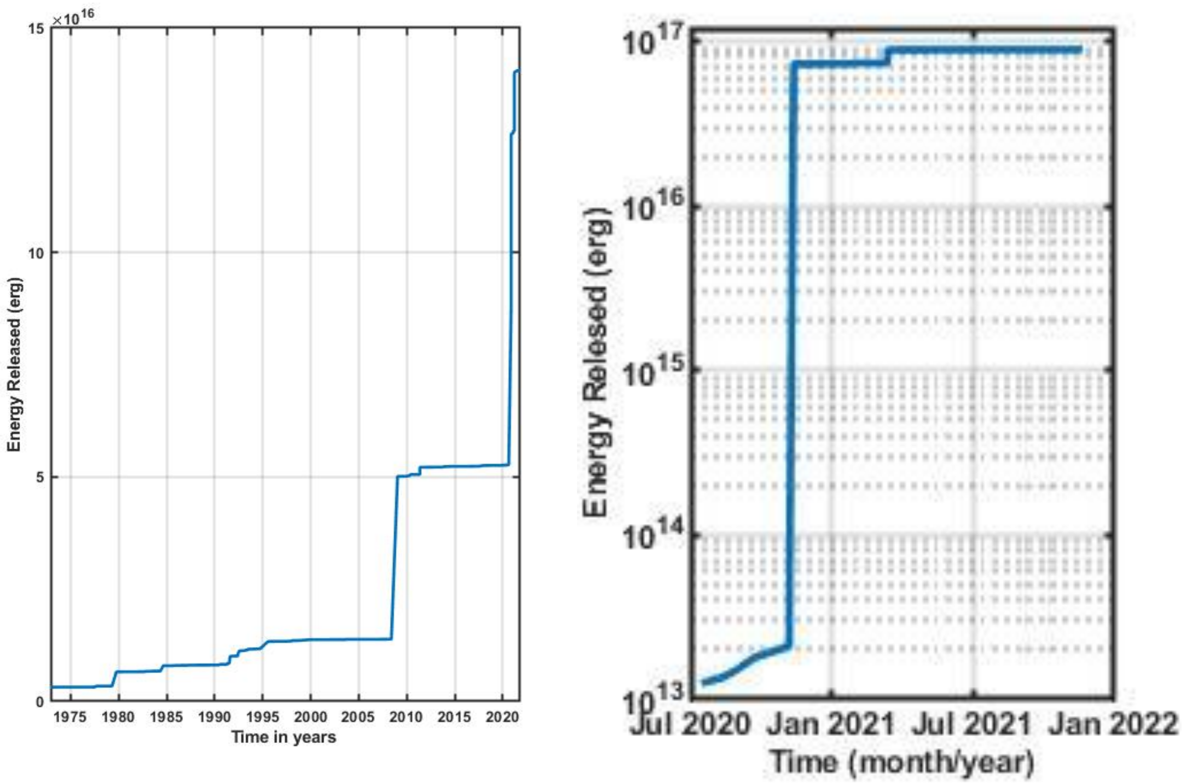


Figure 6: Color-coded values of coefficients a and b for the Mavrovo polygon.

Rather than the number of earthquakes, when the catalogue contains sparce data, then the patterns of seismicity are better represented through the cumulative energy release. Therefore, the released energy of the earthquakes E i.e. the seismic potential can be calculated from their magnitude, using the formula (3) (www.usgs.gov):

$$\log E = 5.24 + 1.44\, M \tag{3}$$

Figure 7a displays the time-dependent Benioff stress release diagram by (3) for the Mavrovo region in the period 1970 until the end of 2021, where energy is represented in units of *ergs*. We observed that after approximately 30 years of relative quiescence (1978-2008) the region enters a period of accelerated seismicity. Latest studies indicate that earthquakes on faults are sometimes preceded by phases of accelerated seismic release characterized by cumulative Benioff strain, following the power law of time-to-failure for different segments. It can be noticed on the diagram that the accumulated stress in the volume was released in roughly two stages, each lasting about a year.



a b

Figure 7: Time-dependent Benioff stress release diagram for the Mavrovo region:
a - (1970-2021); b – (Jul 2020-Nov 2021).

Figure 7b similarly shows the time-dependent Benioff stress release diagram for the Mavrovo region in more details, for the period Jul 2020 until Nov 2021, where the energy is represented in *ergs* and plotted on Y-axes in logarithmic scale.

Based on the diagram, it can be noticed that the accumulated stress in the volume was released in two quick stages, each lasting a day. The average hypocentral depth of the events is concentrated in the top 20 km, which is an indication of a relatively old and brittle shallow crust in the Mavrovo region.

Plane solutions for the strongest earthquakes in the seismic sequence Jul 2020–Nov 2021, were computed by SORM using FP software (Herak, 2014). These seismological data confirmed the source mechanisms for the two strongest earthquakes as normal faulting (Drogreshka et al., 2021), which had striking toward NNE. That faulting is associated with the neotectonic Mavrovo fault, which is part of the seismically active Skopje-Kustendil fault system. Thus, the shape of the isoseismal map (Fig. 4) and the solutions of the mechanisms of the two strongest earthquakes (Fig. 8) are in agreement with the tectonic data of the active faults, point towards NNE extension.

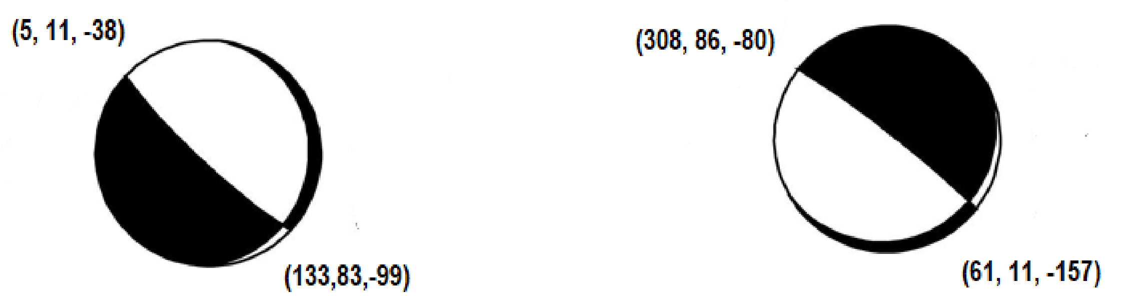


Figure 8: Fault plane solutions for the two strongest earthquakes in Mavrovo region (Jul 2020–Nov 2021).

According to the map of the maximum expected intensities for return period of 100 years (Jordanovski et al., 1998), the region can experience an intensity of VII (MSK-64), which might be equivalent to an event of magnitude M=5.1±0.3.

DISCUSSION AND SUMMARY

The main goal for our pattern analysis was to investigate the recent change of seismicity with time for a designated region in northwestern Macedonia. For this purpose, the SORM catalogue and the two strongest earthquakes with magnitude M_L5.0 which occurred on 11th of November 2020 near the Mavrovo lake, were considered.

Mavrovo lake is an artificial reservoir with a dam built some 70 years ago. We studied the common factors which might be causing earthquakes, such as local geology and seismotectonic regime in the region. Seismic events of moderate size can have various sequences of foreshocks and aftershocks, which mostly depend on the earthquake mechanism.

In this case, a numerical analysis was done for the first time from the list of events reported by the Skopje Seismological observatory, that happened about six months prior to the strongest events and one year after, till November 2021. A selected list of over 100 earthquakes registered by the local and regional stations with magnitudes equal or greater than $M_L 1.7$ was analysed in more details in terms of temporal and spatial distribution around the lake, in a polygon area defined by geological features.

We observed that the accumulated stress in the volume between 1970-2021 was released in roughly two stages, each lasting about a year, while for the period Jul 2020 until Nov 2021, the regional stress was released in two quick stages, each lasting a day. No statistically significant clustering of events was noticed in the foreshock period from July 2020. In the aftershock period, the most numerous events lasted about a month after the main events. However, there was another period of increased seismicity during March 2021, followed by gradual decrease onwards.

Because the current value of the released energy is less than the hundred-years seismic cycles, it can be speculated that the region has potential to experience larger earthquakes in foreseeable future. The results of this study may affect the seismotectonic models presently used for that section of the faults and help in the earthquake hazard assessment on regional and wider scale.

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REFERENCES

Arsovski. M. (1996). Tectonics of Macedonia, Faculty of mining and geology, Goce Delcev University of Stip, Macedonia.

Arsovski. M., and Hadzievski. D. (1970). Correlation between neotectonics and seismicity of Macedonia, Tectonophysics, Vol. 9, pp. 129-142, Netherlands.

Chernih, D., Drogreshka, K. and Najdovska, J. (2021). Seismic Activity in the Tetovo-Gostivar Epicentral Area in the period between November 2020-March 2021. 37th General Assembly (GA) of the European Seismological Commission, poster presentation.

Drogreshka, K., Najdovska, J., Chernih-Anastasovska, D., Jovanov, Lj., Andreeska, M., and Molerovikj, I. (2021). Series of earthquakes from November 2020 to March 2021 between Tetovo-

Gostivar and Kicevo epicentral area. 13th Conference of the Society of Physicists of Macedonia 2021, ISBN: 978-608-4711-12-4.

Dumurdjanov, N., Milutinovic, Z., and Salic, R. (2020). Seismotectonic model backing the PSHA and seismic zoning of Republic of Macedonia for National Annex to MKS EN 1998-1:2012 Eurocode 8. Journal of Seismology, ISSN 1383-4649, Volume 24, Number 2, 24:319-341 DOI 10.1007/s10950-020-09912-9.

Iliovski, Z., Mirčovski, V., Petrov, G., Spasovski, O., and Nikolov, S. (2003). Neotectonic and seismotectonic features of the Pelagonian, Kičevo and Poreč depressions and the surrounding block structures, Geologica Balcanica, 33, 3-4, pp.49-56. Sofia, Dec. 2003.

Jancevski, J. (1987). Classification of the normal fault structures according to their origin age and morphology and in respect to their seismicity on the territory of Macedonia, PhD thesis (in Macedonian).

Jordanovski, Lj., Pekevski, L., Chejkovska, V., Chernih, D., Hristovski, B., and Vasilevski, N. (1998). Basic characteristics of seismology on the territory of Republic of Macedonia (in Macedonian). Seismological Observatory of the Faculty of Natural Sciences and Mathematics, University Ss. Cyril and Methodius, Skopje, Macedonia, report No. 1998-01.

Herak, M., 2014, FPS Software, Faculty of Science, Department of Geophysics, Zagreb University

Herak, M., Herak, D. and Orlić N. (2021). Properties of the Zagreb 22 March 2020 earthquake sequence – analyses of the full year of aftershock recording, Geofizika Vol.38, DOI: https://doi.org/10.15233/gfz.2021.38.6, Zagreb, Croatia.

Sinadinovski, C., and McCue, K. F. (2000). Recurrence relationship for Australian earthquakes, Australian Earthquake Engineering Society Conference AEES, pp. 22, Hobart, Tasmania, Australia.

SORM – Annual earthquake catalogues (1970-2021), Seismological Observatory of the Faculty of Natural Sciences and Mathematics, University Ss. Cyril and Methodius, Skopje, Macedonia.

Stejskal, V., Lorenzo, F., Pousse, G., Radovanovic, S., Pekevski, L., Dojcinovski, D., Lokin, P., Petronijevic, M. and Sipka, V., 2010, Probabilistic Seismic Risk Model for Western Balkans, EGU General Assembly 2010, p.12983. (A poster.), 2-7 May 2010, Vienna, Austria.

Wiemer, S., 2001. A software package to analyze seismicity: ZMAP. Seismological Research Letters, 72(3), pp.373-382 https://doi.org/10.1785/gssrl.72.3.373