УДК 550.34, 550.394 DOI: https://doi.org/10.24028/gj.v46i1.298659

Reservoir-triggered seismicity: case study of the Dnister Hydro Power Complex (Ukraine)

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Received 9 October 2023

The work considers the seismic activity around the Dnister Hydro Power Complex in the Dnister Reservoir area from 2012 to 2021. Maximum local magnitude of earthquakes for the studied period is M_L=3.4. Hypocenters of earthquakes are at the depth of 1—3 km. They are located nearby to previously established faults and contacts of structures with a different lithological composition. Artificial water level regulation in the reservoir is related to the operation of the Dnister Hydro Power Plant and, according to our results, probably affects the occurrence of seismic events. Although the maximum water level changes only by 8.7 m, the region has increased natural seismicity and is located in the transition zone between 6^{th} and 7^{th} isoseims according to the seismic zoning map of Ukraine. Accumulated natural stresses can be triggered into earthquakes when there is a sudden change in water pressure. The seismicity of the region around the Dnister Reservoir was investigated for 10 years, taking into account the water level data in the reservoir, as well as comparing the location of earthquakes with the State Geological Map of the Crystalline Foundation. The profile of the State Geological Map of the Crystalline Foundation with the projected earthquakes hypocenters allowed to indicate that a significant number of earthquakes are located between different lithological structures. In order to assess the interrelationship between seismicity and water level changes in the reservoir, 111 periods of lowering or filling of the reservoir were selected. Parameters of seismic activity within the periods were calculated and analysed. Correlation between the sum of logarithms of energy with water volume changes and pressure changes in the Dnister Reservoir was established. Considering linear dependence it is possible to predict potential intensity of local seismicity caused by water level changes in the Dnister Reservoir.

Key words: Reservoir-triggered seismicity, water level changes, Dnister Hydro Power Complex, Dnister Reservoir.

Introduction. Reservoir-triggered seismicity (RTS) is a well-known phenomenon associated with water storage and its seasonal fluctuations in artificial lakes. The initiation of earthquakes by artificial reservoirs was first observed in Lake Mead, USA [Carder, 1945; Gupta, 2002]. Some artificial reservoirs can cause earthquakes immediately after they are filled or have a seasonal trend [Gupta, 2002]. Earthquakes can also appear during their operation due to changes in the water level, excess pressure, and changes in geological stress. Analysis of the relationship between temporal water level changes and seismicity in the Mingechevir Reservoir (Azerbaijan) statistically confirms that the seismicity occurring in the area can be caused by the annual cycle of the reservoir water level [Telesca et al., 2020]. Its rise had a decisive effect on seismic activity in the upper part of the Three Gorges Reservoir in China [Meng et al., 2022].

Further gravity observations and numeri-

Citation: *Tretyak K., Brusak I., & Pronyshyn R.* (2024). Reservoir-triggered seismicity: case study of the Dnister Hydro Power Complex (Ukraine). *Geofizicheskiy Zhurnal*, *46*(1), 38—51. https://doi.org/10.24028/gj.v46i1.298659.

cal modeling showed that the seismic activity was directly related to the overburden pressure caused by the rapid rise of the water level in the reservoir. This led to the instability of mines, karst caves, shallow rock layers, and faults within 10 km distance along rivers and reservoir banks, and therefore caused earthquakes. After the 2013 Xiluodu Reservoir flooding in China, researchers [Chang et al., 2022] indicated an increase in the average released energy of earthquakes. These studies confirm the relationship between the water level changes in large reservoirs and the triggered seismicity around them.

Most artificial reservoirs were created in regions with low seismicity for safety purposes. Earthquakes of minor magnitude cause water level changes in reservoirs. In most cases, their local magnitude is within M_L=2÷4. However, there are also examples of powerful destructive earthquakes near reservoir dams in India [Jiménez et al., 2009]; in such cases, seismic activity can lead to casualties and significant destruction of infrastructure. Therefore, conducting a detailed investigation of each object that can cause seismicity is important. Another crucial problem is predicting the dangerous zones of the RTS. Distinguishing between natural and triggered seismicity remains a challenging task that requires developing specific criteria [Oprsal, Eisner, 2014].

The mechanism responsible for RTS involves elastic increases in shear or reducing normal stress following reservoir filling, pore pressure increase due to diffusion, and coupled poroelastic phenomena due to compaction [Gupta, 2002; McGarr, Simpson, 1997]. The basic mechanism associated with RTS is attributed to an increase of pore pressure along faults that are already close to critically stressed by the ambient tectonic stress. Other effects include poro-thermoelastic effects and change in gravitational loading on fault systems without the necessity of a hydrologic connection. A mechanism of increasing earthquake strength due to reservoir filling is unlikely since the formation pressure of reservoirs is too small to rupture the Earth's crust [Srivastava, 1993]. The response of activity and its delay to water level changes and increased hazard during the gap period suggest that the main triggering factor is pore pressure change due to the significant water level changes in Song Tranh 2 reservoir, Vietnam.

The volume of the reservoir plays an important role. According to RTS studies in Brazil, the minimum reservoir volume value should be at the level of 10^{-4} km^3 for seismicity to occur. Magnitude 4.2 was observed in a reservoir with a volume of more than 10^{-3} km^3 [Sayão et al., 2020].

Despite the importance of reservoir volume for RTS studies, there is a more objective reservoir characteristic. It involves the ratio of reservoir volume to surface area. This ratio correlates with reservoir pressure.

The magnitude of formation pressure causes seismic activity. It depends on a spatial network of faults with heterogeneous permeability fields. The findings obtained from reservoirs located on different continents have significant discrepancies regarding the minimum value of reservoir pressure. The RTS observation was conducted at the Asu Reservoir in north-eastern Brazil. It was established that the manifestation of seismic events becomes possible when the formation pressure at hypocentral depths changes by 0.05 kPa [Lunn et al., 2004]. According to data from the Koyna and Varna Reservoirs in India, an increase of reservoir pressure by 300—600 kPa caused 19 earthquakes of magnitude over 5.0. In addition, earthquakes with M≥3.0 in the region are associated with reservoir pressure changes of 100—200 kPa [Gupta, 2002].

Beneath the Jocassi Reservoir in South Carolina, earthquakes with a magnitude of 2.0≤M≤3.0 occurred in homogeneous crystalline rock with no cracks. They were associated with an additional formation pressure of 600—700 kPa. Earthquakes of 2.0≤M≤3.0 occurred in the same region in the areas with very complex geology and dense cracks near the Monticello Reservoir, where formation pressure values were within 100 and 300 kPa [Dura-Gomez, 2009]. RTS was observed after the 1967 flooding of the Danjiangkou Reservoir in Henan and Hubei provinces in central China. Starting with a low level of seismicity, the magnitude increased with the growth of the lake level and caused the 4.7 magnitude earthquake in November 1973. The pressure change of ~300 kPa triggered earthquakes M>4.0 in the Danjiangkou Reservoir area [Liu et al., 2011]. Seismicity increased in reservoirs located in karst areas. Thus, seismicity in the central-western Pyrenees in Spain was caused by the Itoiz Reservoir flooding in 2004. In this area, the induction of M≥3.0 earthquakes was associated with the diffusion of rising reservoir pressure up to ~100—500 kPa along Early and Middle Eocene carbonate megabreccia systems [Dura-Gomez, Talwani, 2009; Dura-Gomez, 2010].

Considering the experience and results obtained by various RTS studies, it can be concluded that the mechanism of triggered seismicity by artificial reservoirs in each case has specific features. It mainly depends on the geological structure of the research area and the parameters of the reservoir, as well as its hydrodynamic characteristics.

The purpose of this work is to investigate the causes of increased seismicity in the area of the Dnister Reservoir. This reservoir was artificially formed to operate the Dnister Hydro Power Plant N1 (HPP-1) in Ukraine.

Research region. The Dnister power complex includes three main facilities: the Dnister HPP-1, the Dnister Pumped-Storage Power Plant (PSPP), and the Dnister HPP-2 (Fig. 1). The Dnister HPP-1 was built in 1981 on the Dnister River. The hydroelectric power plant is designed for electricity production, prevention of flooding due to snow melt, land irrigation, and water supply to populated areas.

The Dnister HPP-1 is of spillway type and has a dam with a length of 1.082 m and a height of 100 m. The power of the Dnister HPP-1 is 702 MW. The total estimated water flow through the drain holes ranges from 6.800 to 11.280 m^3/s. The volume of the reservoir is 3.0 km^3, the area of the catchment basin is 40,500 km^2; the length is 194 km; the average depth is 21.0 m; the maximum depth is 54 m.

The general view of the Dnister HPP-1 and the reservoir is shown in Fig. 2. The reservoir was filled during from 1981 to 1987, which was

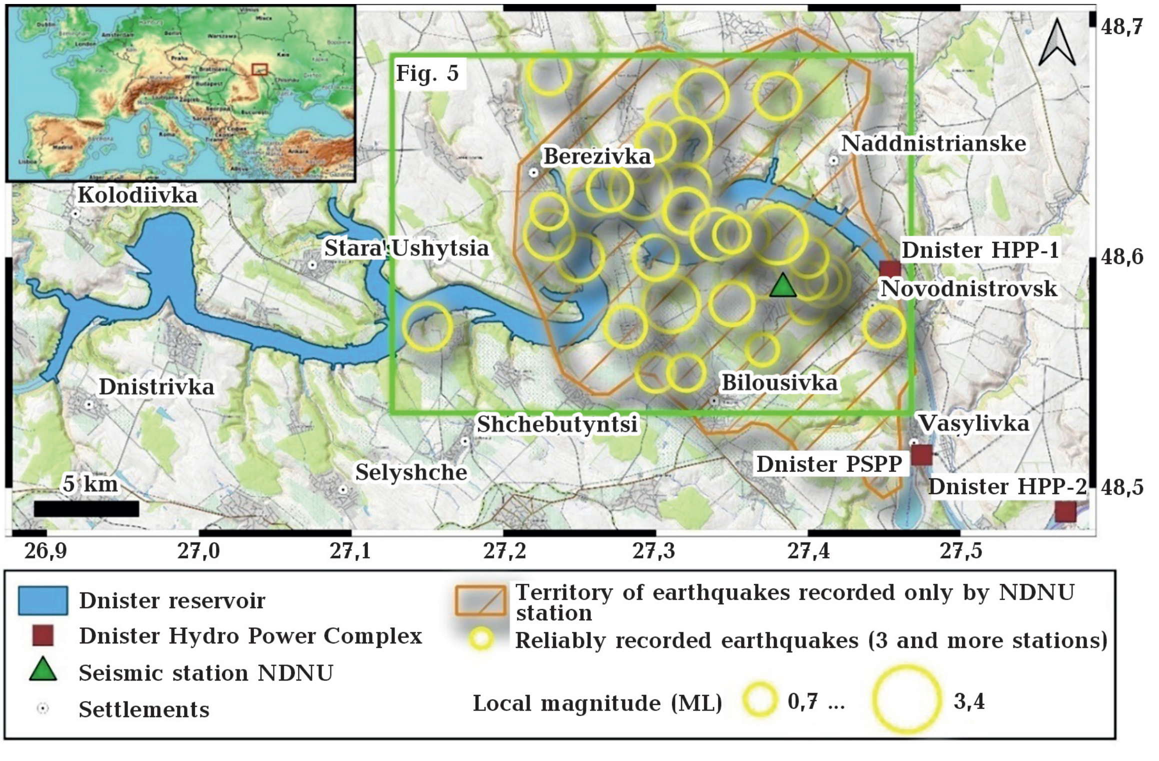

Fig. 1. Research region with objects of the Dnister hydropower complex, the seismic station «Novodnistrovsk» (NDNU), and earthquake epicenters around the upper Dnister Reservoir from 2012 to 2021.

explained by a long period of water shortage.

The Dnister Hydropower Complex is located on the outskirts of the southwest part of the Eastern European Platform within the bounds of the Volyn-Podillya and Moldavian plates with the presence of the Ukrainian shield [Savchyn, Pronyshyn, 2020]. The shield is cut off by the Podillya fault zone, which is the southwest boundary of the Ukrainian shield. The Podillya fault zone of over 320 km is oriented in the north-west direction and

Fig. 2. General view of the Dnister HPP-1 and the reservoir [Online source: Official site of Dnister Water resources management].

is fraught with faults of the north-west and north-east stretch. According to [Sarnavski, Ovsiannikov, 2005], the faults are characterized by discharges with an amplitude of 50—100 m in the area of joining between the Ukrainian Shield and the Volyn-Podillya Plate. Much of the fracture breaks the thickness of the Neogene-Quaternary deposits and is connected with the activation of a more ancient layer.

There is regular monitoring of the modern geodynamics of the Dnister Power Hydro Complex and its influence on deformations of engineering structures [Sidorov et al., 2015; Savchyn, Vaskovets, 2018; Savchyn, Pronyshyn, 2020; Tretyak et al., 2021a,b]. Special tectonic studies of the region [Sarnavski, Ovsiannikov, 2005] suggest that the reservoir filling causes an increase in the pressure on the sides of the Dnister Valley. This leads to the deflection of the bed and an increase in the slope, thus triggering earthquakes.

Savchyn and Pronyshyn [2020] indicate the presence of induced seismicity in the studied region, which includes all the power complex facilities. The seismicity is associated with the continued construction of units of the Dnister PSPP. However, this statement is based only on comparing long-term series of seismicity and deformations of the Dnister Hydro Power Complex region. Dnister PSPP is located outside the main zone of seismicity. Another research [Zyhar et al., 2023] confirms the relevance of studying the impact of water level fluctuations on the geodynamic situation in the Dnister Hydro Power Complex, as well as the importance of continuous monitoring and development of risk management measures. This study looks closer at the Dnister HPP-1 region, in particular by expanding the earthquake database.

Background seismicity in the reservoir area. The area of the Dnister Hydro Power Complex is seismically active. According to the seismic zoning map of Ukraine, it falls into the transition zone between isoseims of 6 and 7 points [DBN V.1.1-12:2014]. During instrumental observations in 1961—2004, 15 earthquakes of local magnitude within 2.0—3.5 were registered by the network of seismic stations in the Carpathian region in the area of the Dnister Hydro Power Complex. The network of seismic stations that existed before 2004 could register only earthquakes with local magnitude M_L>2.0. Weak earthquakes in the area of the Dnister power complex were not recorded due to the lack of seismic stations. At that time, the three nearest seismic stations («Chernivtsi», «Horodok» and «Kosiv») were located 100—200 km west of the Dnister power complex [Verbitskyi, Verbitskyi, 2011]. The velocity model [Kutas et al., 1999] is used in the Carpathian region.

Fig. 3 shows a network of seismic stations in Ukraine and Moldova that could be used to study seismic events near the Dnister Hydro Power Complex. Not all stations record every earthquake in the studied region.

In recent years, the seismic station «Novodnistrovsk» (NDNU) has been operating in the Dnister Hydro Power Complex area. The station belongs to the seismic network of the Carpathian region (Ukraine), which has 20 seismic stations [Verbytskyi, Verbytskyi, 2011]. NDNU station was installed in October 2005 in Lomachynci village, Chernivtsi region. Digital automatic seismograph DAS-05 with a magnetoelectric seismic receiver

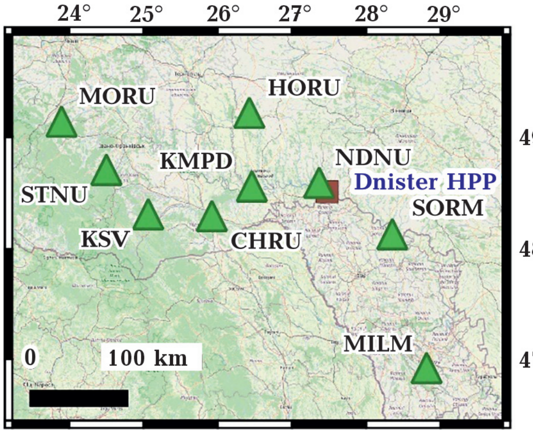

Fig. 3. Network of seismic stations in Ukraine and Moldova for earthquake studies near the Dnister Hydro Power Complex.

SM-3KV is used as the main module at the station. It registers vibration parameters along orthogonal components North-South, East-West, and vertical in the dynamic range up to 140 dB. It also synchronizes the arrivals of seismic waves with GPS time. The equipment has a guaranteed power supply system with automatic switching and is configured for automatic processing and analysis of regional seismic information [Verbytskyi et al., 2019]. Seismic data is processed by the Department of Seismicity of the Carpathian region of the S.I. Subbotin Institute of Geophysics of the National Academy of Sciences of Ukraine [Online source: Official site of the National Academy of Science of Ukraine].

The database in the study includes earthquakes recorded by the seismic network (see Fig. 3) as well as only by the seismic station «Novodnistrovsk» (see Fig. 1).

Fig. 4 shows data on the annual distribution of the number of earthquakes N and the logarithm of the total seismic energy E in joules ($\lg(\sum E)$), which was released in the area of the Dnister energy complex for the period 2012—2021.

As seen in Fig. 4, the maximum number of earthquakes occurred in 2014—2016, and the maximum energy was released in 2016. In the following years, there was a decline in both the number of earthquakes and the total released energy. A change in the number of seismic events may indicate a redistribution of the stress-strain component accompanied by a violation of rock integrity. Such processes are natural and reflect the rock's response to technogenic intervention and possible changes in the water level.

For the period from 2012 to 2021, 956 earthquakes were recorded in the area of the Dnister Hydro Power Complex. This number includes 36 earthquakes registered by three or more seismic stations. Table 1 presents a catalog of reliably registered earthquakes in the Dnister reservoir area from 2012 to 2021. The reliably recorded minimum local magnitude is M_L=0.7.

The epicenters of all earthquakes of

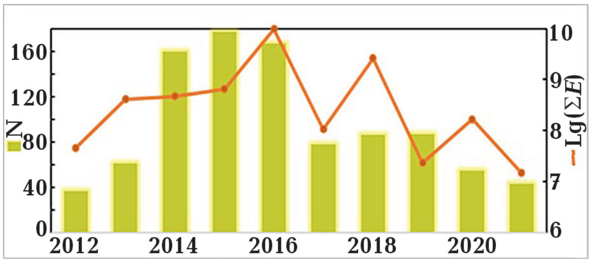

Fig. 4. Distribution of the number of earthquakes N and the logarithm of the total seismic energy E in joules ($\lg(\sum E)$) released in the Dnister reservoir area during 2012—2021.

2012—2021 were located in the eastern part of the Dnister Reservoir (see Fig. 1). Only 36 earthquakes were reliably recorded in the study area during 2012—2021 (yellow circles in Fig. 1). This amount of data is not enough to detect any statistical relationships. Therefore, we took into account weak earthquakes in the zone highlighted in orange (see Fig. 1) and determined according to the data of one NDNU station [Brusak et al., 2022]. Those weak earthquakes have a magnitude in the range of 0.1—1.3, and the hypocenters of earthquakes are at a depth of about 2 km.

Data from 751 earthquake epicenters located within a radius of 5 km from the borders of Dnister Reservoir was used in further

Table 1. Catalog of reliably registered earthquakes in the Dnister reservoir area from 2012 to 2021

№	Year	Month	Day	Time at hypocenter			Coordinates		Depth, km	Magnitude, M_L
				Hour	Minutes	Seconds	Latitude N	Longitude E		
1	2012	10	23	08	56	19	48.60	27.25	3.0	2.0
2	2013	2	16	13	33	58	48.66	27.31	3.0	2.1
3	2013	2	23	18	03	17	48.67	27.33	2.0	2.5
4	2013	7	13	23	45	33	48.6	27.4	2.0	1.7
5	2014	4	12	15	32	52	48.64	27.29	2.0	0.8
6	2014	4	29	01	42	46	48.55	27.30	2.8	1.3
7	2014	5	26	08	37	03	48.58	27.40	2.0	1.3
8	2014	5	28	16	52	32	48.56	27.37	1.0	0.7
9	2014	6	10	21	49	38	48.65	27.32	1.3	2.0
10	2014	7	18	13	50	35	48.59	27.37	2.3	0.9
11	2014	7	19	05	03	08	48.59	27.41	1.9	2.5
12	2014	7	19	10	51	06	48.59	27.41	2.1	0,9
13	2014	7	19	15	10	58	48.59	27.40	2.4	1.1
14	2014	7	22	16	17	38	48.55	27.32	2.0	1.1
15	2014	8	12	04	00	42	48.6	27.4	2.8	1.5
16	2015	4	23	07	26	35	48.63	27.26	2.0	2.3
17	2016	2	7	17	06	53	48.58	27.31	4.0	2.9
18	2016	2	8	4	46	39	48.63	27.32	2.0	2.2
19	2016	3	9	23	4	57	48.61	27.23	5.0	2.2
20	2016	5	5	06	57	47	48.68	27.23	2.0	1.5
21	2016	7	12	18	21	52	48.63	27.29	2.0	3.4
22	2017	3	4	04	04	29	48.60	27.30	1.1	1.8
23	2017	5	25	19	17	48	48.67	27.37	3.2	1.6
24	2017	6	14	21	47	13	48.62	27.23	2.0	0.9
25	2017	7	8	22	25	21	48.62	27.32	2.0	1.7
26	2017	11	26	04	48	46	48.61	27.36	2.0	1.6
27	2018	1	17	04	14	28	48.63	27.27	2.0	1.6
28	2018	3	24	12	20	54	48.61	27.38	1.0	2.6
29	2018	5	31	13	4	12	48.58	27.35	2.5	1.7
30	2018	7	20	4	30	28	48.57	27.15	2.0	2.0
31	2018	12	27	19	39	41	48.62	27.32	2.0	1.7
32	2019	5	16	22	45	04	48.64	27.30	2.0	1.2
33	2020	5	20	15	20	42	48.61	27.34	1.3	2.0
34	2021	2	5	00	51	27	48.57	27.45	2.0	1.4
35	2021	12	26	21	45	23	48.61	27.35	2.0	0.8
36	2021	12	29	11	50	48	48.57	27.28	2.0	1.7

research. The data was chosen as a buffer in QGIS software.

Location of earthquakes on the geological map of the region. In order to review the probable nature of earthquakes, we will consider the geological map of the crystalline basement on a scale of 1:200.000 in this region [State…, 2007]. According to the zoning scheme of the Precambrian formations, the region belongs to the Sokyryan subzone and the Bakhtyna trough structure. There are the following local stratigraphic subdivisions and complexes of the Precambrian basement (from top to bottom):

– the Berdychiv complex of the Paleoproterozoic era of the Proterozoicis composed of granites and migmatites ($\gamma_1 PR_1^1 bd$ in Fig. 5, 6), porphyry biotite granites with apatite and magnetite ($\gamma_1 PR¦bd$ in Fig. 5, 6), hypersthene-garnet-biotite migmatites, sometimes granite-vinnitites ($\gamma_1 PR¦bd$ in Fig. 5, 6), charnockitoids and magmatites;

– the Mikhalkiv association of basites and ultrabasites of the Neoarchean era of the Archaean, which is composed of pyroxenites (υAR_3mh?);

– the Lityn complex of the Mesoarchean era of the Archaean is composed of enderbites, cherno-enderbites;

– the Berezny Formation of the Paleoarchean era of the Archaean is mainly composed of garnet-biotite-sillimanite- and cordierite-containing gneisses, as well as biotite, graphite-biotite, and sillimanite-biotite.

Fig. 5 shows only reliably recorded earthquakes on a 1:200.000-scale geological map of the crystalline basement. An explanatory note contains a detailed description of the notations for the geological map and the mineral map of the crystalline foundation [State…, 2007].

The ABCD profile [State …, 2007] passes SW-NE through the studied territory (see Fig. 5). The selected geological map of the crystalline foundation includes sediments up to 10 km deep. It is satisfactory for considering hypocentres of 1—5 km depth in this region. ABCD profile consists of segments AB, BC, and CD. For each of these segments, the coordinates of the vertices A, B, C, and D are known. Based on this, we can calculate the segment's azimuth and perpendicular azimuth. The line with the known azimuth is drawn from each point (earthquake) that forms the 90° angle with the profile segment. The intersection of these two lines is the perpendicular projection of the epicenter onto the profile. To identify the hypocenter, the depth of the earthquake is used. In Fig. 6, reliably recorded earthquakes with known magnitude are projected onto the geological profile ABCD.

Figs. 5 and 6 show that the location of earthquakes only partially corresponds to recorded and probable faults. The profile demonstrates that part of the earthquakes is located between two structures formed in the Proterozoic. They have different compositions. This is typical for the region where the profile line crosses the Dnister reservoir.

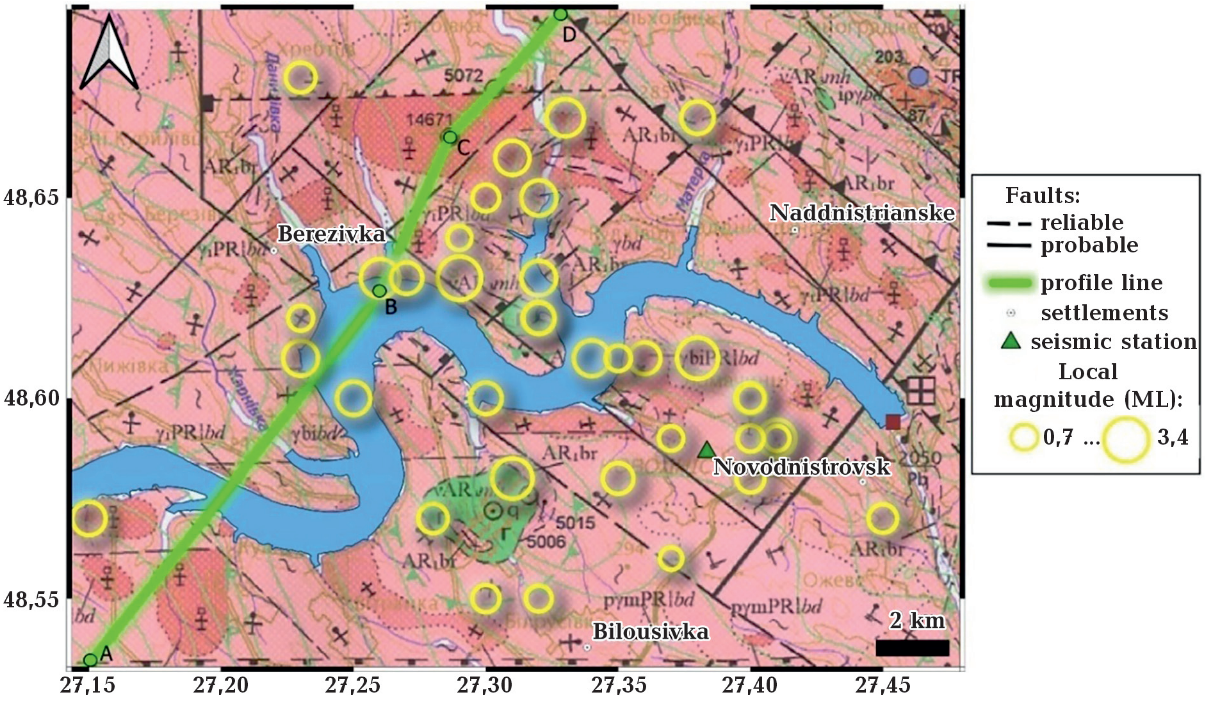

Fig. 5. Epicenters of reliably recorded earthquakes from 2012 to 2021 around the upper Dnister reservoir on the geological map of the crystalline foundation [State…, 2007].

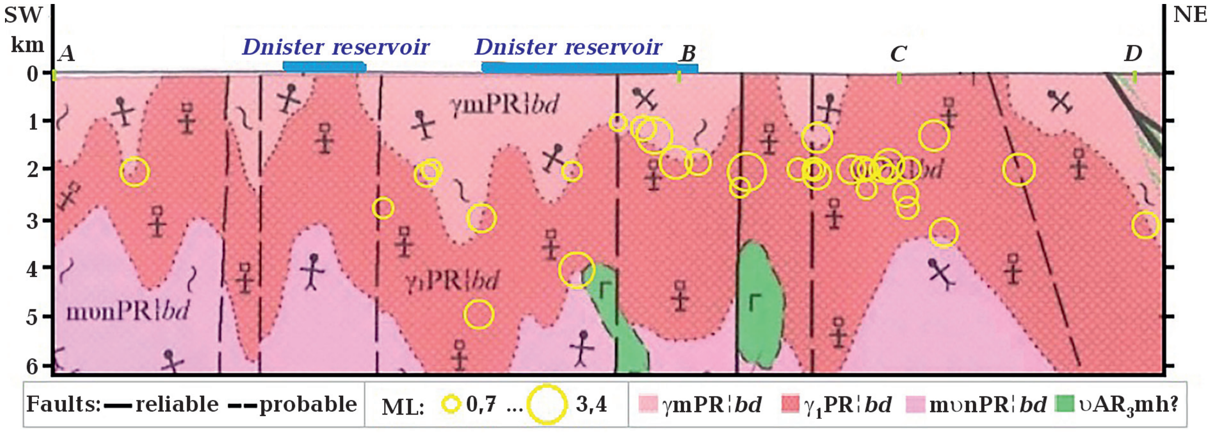

Fig. 6. Hypocenters of reliably recorded earthquakes from 2012 to 2021 on the geological profile of the crystalline basement [State..., 2007]. Geological sediments: Proterozoic granites and migmatites ($\gamma_1 PR_1^{\,}bd$), Proterozoic porphyry biotite granites with apatite and magnetite (γmPR¦bd), Proterozoic hypersthene-garnet-biotite migmatites (*mυnPR¦bd*), Archaean Mikhalkiv association of basites and ultrabasites composed of pyroxenites (υAR_3mh?).

The depth of most recorded earthquakes is 1—3 km. They are mostly concentrated in the contact zone of rocks composed of granites and migmatites (*γmPR¦bd*), as well as porphyritic biotite granites with apatite and magnetite (γ_1*PR¦bd*). The contact zone activity may be triggered by the fact that there are more cracks and weak zones in such an interface.

Pore pressure causes an increase in the shear stress, and small discontinuities located near the interface start to slip. Given the shallow depth and the features of the earthquake hypocenter location, it can be assumed that seismicity results from pressure changes created by the water masses of the upper Dnister reservoir.

Relationship between the regional seismicity and reservoir volume changes. The water level in the reservoir depends primarily on the operation of HPP-1 and the Dnister Hydro Power Complex as a whole. For example, when needed, several meters of water can be released from the reservoir, which is in a volume equivalent to great changes in the load on the earth's surface.

The research uses information on the upper reservoir level change of the Dnister HPP-1. It includes the automatically recorded hourly data since September 2016. Archival data on the water level was recorded daily from 2012. The lowest level in the reservoir was 112.92 m in 2015. The highest level of 121.62 m was recorded in 2018. Thus, the difference between the highest and lowest levels during the observation period was 8.70 m, corresponding to a change in pressure difference of 87 kPa. The average water level for those years was 118.56 m.

Fig. 7 shows a time series of water level changes and manifestations of all earthquakes at a distance of up to 5 km from the Dnister Reservoir from 2012 to 2021. Seismicity is generalized by the parameter of the sum of the energy of earthquakes every 2 months. The red curve represents the logarithm of the total released energy of earthquakes ($\lg(\sum E)$).

Fig. 7 indicates that water level changes in the reservoir do not have a clear seasonal nature. The red and blue curves in some periods show common dynamics of changes, which may demonstrate a relationship. There are also noticeable periods in 2016—2017 when the dynamics of reservoir level and seismic energy are different.

Based on the data, it is also possible to calculate the volume changes in the reservoir. Since the change in the reservoir water level is known, we can establish the area of the reservoir mirror. We will use the reservoir area within which seismic activity occurred from 2012 to 2021. For this purpose, the limits of the Dnister Reservoir are set in the QGIS environment. The approximate area of its flooding is selected based on the Open TopoMap

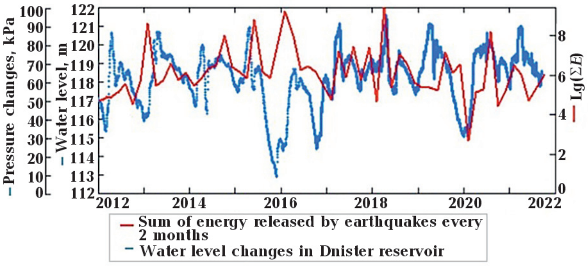

Fig. 7. Time series of the amount of energy released by earthquakes every 2 months as well as changes in both water level and pressure of the Dnister Reservoir from 2012 to 2021.

model of the area. The area of the reservoir site is S_{min}=34.5 km^2 at the lowest water level. With the maximum change in the water level of 8.70 m, the reservoir mirror increases by 2.6 km^2.

The lowest water level is taken as the conventional zero level. Since the estimation is approximate, the reservoir can be represented as an equilateral trapezoid in cross-section. When calculating the volume, we take into account that it is not directly proportional to the growth of the water level in the reservoir.

The first approach to finding the relationship included dividing the studied period into equal phases, e.g., monthly. The integral daily change of water volumes and the sum of the released earthquake energy were calculated within a month. A search for correlation was performed when the periods changed from 1 to 5 months. However, such a correlation relationship was not found (r=0÷0.1).

The second approach included defining periods of unidirectional changes in the reservoir water level. Thus, this helped to distinguish 111 periods of growth and decline in the water level. Accordingly, we calculated the number of earthquakes N and the sum of logarithms of earthquake energy $\sum \lg E$.

In order to find correlations between the water level change in the reservoir and the total seismicity, one should use the sum of logarithms of energy ($\sum \lg E$) but not the logarithm of total earthquake energy ($\lg(\sum E)$). Similarly, the study [Tretyak, Romaniuk, 2018] established stable correlation relationships (r=0.95) between the sum of earthquake magnitudes with vertical territory deformations shown by the integral velocity index of the vertical displacement from 2000 to 2011. Such an approach was used to study the relationship between seismicity and modern horizontal displacements of the Earth's crust. It also allowed the identification of correlational relationships between parameters [Tretyak, Brusak, 2020].

Table 2 presents the periods of unidirectional changes in the reservoir water level. It also demonstrates the number and sum of logarithms of energy recorded within a radius

Table 2. An excerpt of the catalog of 111 periods of unidirectional pressure and water volume changes in the reservoir when the earthquakes were observed within a radius of 5 km from the Dnister reservoir from 2012 to 2021

№	Initial era T1, years	Final era T2, years	Pressure changes ΔP, kPa	Reservoir volume change, $\lvert\Delta V\rvert$ 10^6 m^3	Sum of earthquake's logarithm energy $\sum \lg E$	Number of earthquakes N
1	2011.996	2012.284	25.9	58.51	13.5	3
2	2012.284	2012.467	26.2	59.12	26.9	6
3	2012.467	2012.571	9.3	33.68	13.8	3
4	2012.571	2012.640	5.3	19.19	8.7	2
5	2012.640	2012.999	27.5	97.76	88.6	20
6	2012.999	2013.327	48.2	171.35	90.3	17
7	2013.327	2013.508	15	54.82	61.4	13
8	2013.508	2013.558	2.7	9.87	23.1	5
9	2013.558	2013.853	15.4	55.69	56	14
10	2013.853	2013.908	4.7	17.00	24	6

of 5 km from the Dnister Reservoir from 2012 to 2021. According to Table 2, the duration of unidirectional changes in the water level in the reservoir lasts from 1 week to 2 months.

Fig. 8 is based on the data from Table 2. Fig. 8, *a* shows the pressure change and the corresponding sum of logarithms of energy $\sum \lg E$. Fig. 8, *b* illustrates the pressure change and the number of earthquakes N during these periods. The width of the blue columns corresponds to the duration of the descent period or the reservoir filling, and the height is the pressure change in absolute value ΔP.

From Fig. 8, there could be some relationship between the parameters. We calculated the Pearson correlation coefficient between ΔP and total seismicity $\sum \lg E$. The coefficient is r=0.78, which may indicate a relationship between the parameters. The correlation coefficient between ΔP and the total number of earthquakes N was calculated, r=0.79. Similarly, we calculated the Pearson correlation coefficient between $|\Delta V|$ and total seismicity $\sum \lg E$ (r=0.70) and $|\Delta V|$ and N (r=0.72). According to the Student t-test, the reliability of the determined correlation was confirmed.

Fig. 9 is based on the data from Table 2. It presents the relationship between the sum of logarithms of energy $\sum \lg E$ and the pressure changes ΔP and volume changes $|\Delta V|$ in the reservoir for the corresponding periods. It shows that this distribution is functionally close to linear.

Accordingly, the interrelationship between parameters will be represented by a linear function:

$$\sum \lg E = a\Delta P + b, \qquad (1)$$

where ΔP are pressure changes in the reservoir, $\sum \lg E$ is a sum of logarithms of energy, and *a* and *b* are constant coefficients.

The coefficients of the linear equation from 111 periods are determined. The equation with accuracy assessment is represented by a linear function (2, 3):

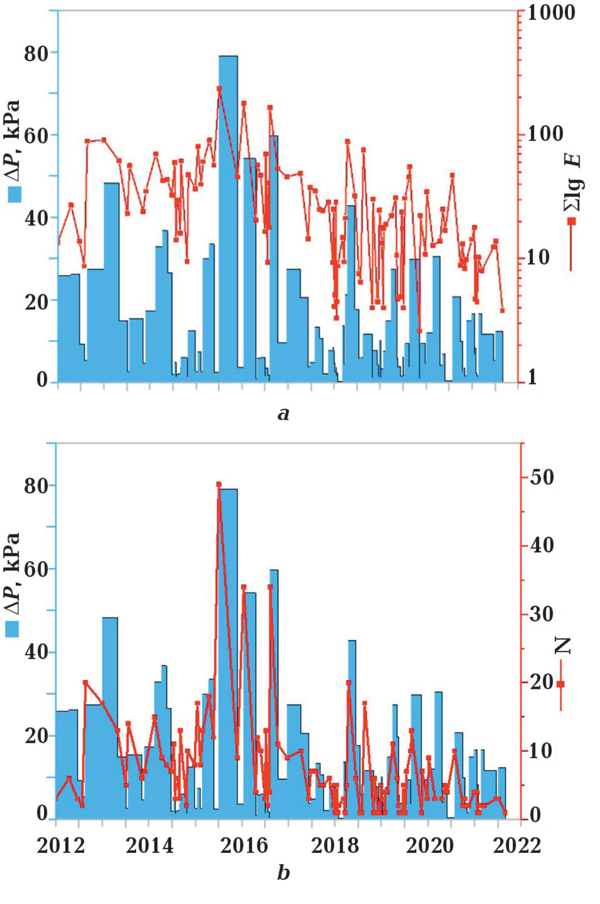

Fig. 8. Water pressure changes of the Dnister Reservoir and the sum of the energy logarithms $\sum \lg E$ (*a*) and the number N (*b*) of earthquakes for the corresponding period from 2012 to 2021.

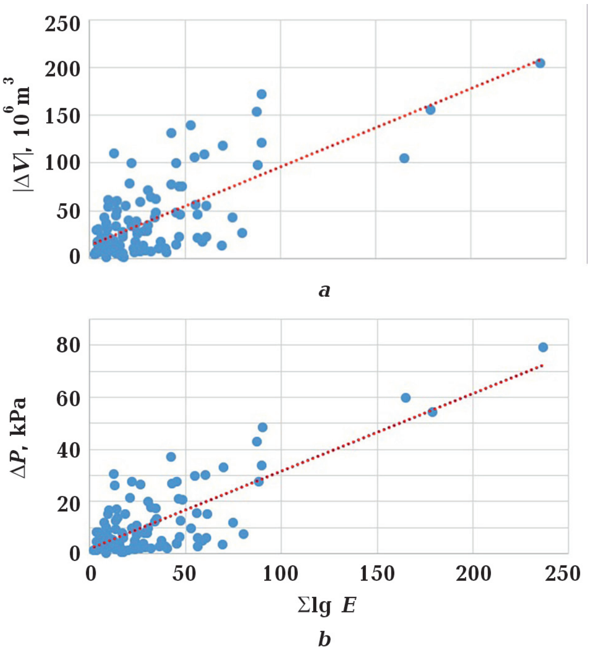

Fig. 9. Linear function of the relationship between the sum of logarithms of energy $\sum \lg E$ and the pressure changes ΔP (*a*) and volume changes $|\Delta V|$ (*b*) in the reservoir for the corresponding periods.

$$\sum \lg E = (2.029 \pm 0.150)\Delta P + (8.94 \pm 0.27)\,, \quad (2)$$

where ΔP are pressure changes in the reservoir, $\sum \lg E$ is a sum of logarithms of energy

The standard deviation of determining the $\sum \lg E$ parameter is 22 when it changes within the limits of 4—236. The value of the approximation probability is R^2=0.6

$$\sum \lg E = (0.597 \pm 0.059)|\Delta V| + (8.09 \pm 3.38)\,, \quad (3)$$

where $|\Delta V|$ is absolute volume changes in the reservoir, $\sum \lg E$ is a sum of logarithms of energy

The standard deviation of determining the $\sum \lg E$ parameter is 28 when it changes within the limits of 4—236. The value of the approximation probability is R^2=0.5.

The interrelationship between pressure changes ΔP and the sum of logarithms of energy $\sum \lg E$ is established more accurately than between absolute volume changes $|\Delta V|$ and the sum of logarithms of energy $\sum \lg E$ for the corresponding periods.

The established correlations show a probable relationship between the water volume and pressure changes in the reservoir and the number and energy of earthquakes formed in the region of the Dnister Reservoir. This connection is clearly not strict. However, it allows us to assert the influence of the water level change of the Dnister Reservoir on the manifestation of local seismicity. In addition, formulas (2, 3) make it possible to predict the intensity of local seismicity when the water level in the reservoir changes due to floods or the technical conditions of the Dnister HPP-1.

Conclusions and discussion. The study considered seismic activity around the Dnister Hydro Power Complex from 2012 to 2021. The work also includes research on the probable impact of the water level changes in the Dnister Reservoir of region seismicity (RIS). The maximum difference between the highest and lowest water levels during the observation period is 8.70 m, corresponding to a change in pressure at the bottom of the reservoir of 87 kPa.

During that period, according to the NDNU seismic station, 956 earthquakes were recorded in the area of the Dnister power complex. In addition, 751 were located within a radius of 5 km from the Dnister reservoir. Only 36 earthquakes were reliably registered by three or more seismic stations with a maximum local magnitude M_L=3.4 in 2016. Most earthquakes were weak, with a magnitude $M_L \approx 0.3 \div 1.0$. Most earthquakes occurred in the eastern part of the reservoir and surrounding areas. The hypocenters of earthquakes were located close to the established faults and contacts of structures of different lithological compositions at a depth of 1—3 km. The hypocenters of earthquakes are concentrated at shallow depths. They were in the contact zone of rocks composed of granites and migmatites and porphyry-like biotite granites with apatite and magnetite.

The study established a correlation of the sum of logarithms of earthquake energy with water pressure changes (r=0.78) and earthquake number (r=0.79) for unidirectional periods from 2012 to 2021. The use of the sum of energy classes ($\sum \lg E$), in contrast to the total energy of earthquakes ($\lg \sum E$), allows us to reveal the relationship. Based on the fact that the interrelationship between the sum of logarithms of energy $\sum \lg E$ with pressure changes ΔP is established as more linear than with absolute volume changes of the reservoir $|\Delta V|$, the assumption about earthquakes triggered by pore pressure mechanism is likely correct. The established linear dependence allows us to predict the possible intensity of local seismicity when the reservoir water level changes during the man-made impact on the Dnister HPP-1 operation.

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Сейсмічність спричинена водоймою: дослідження на прикладі Дністровського гідроелектрокомплексу (Україна)

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У статті розглянуто сейсмічну активність навколо Дністровського гідровузла в районі Дністровського водосховища з 2012 по 2021 р. Максимальна локальна магнітуда землетрусів за досліджуваний період становить: M_L=3,4. Гіпоцентри землетрусів розміщуються на глибині 1—3 км, поблизу раніше виявлених розломів і контактів структур з різним літологічним складом. Штучне регулювання рівня води у водосховищі пов'язане з роботою Дністровської ГЕС-1, за результатами дослідження ймовірно воно впливає на виникнення сейсмічних подій. Максимальні зміни рівня зміни сягають лише 8,7 м, проте цей регіон має підвищену природну сейсмічність і потрапляє до перехідної зони між ізосеймами 6 та 7 балів згідно з картою сейсмічного районування України. Відповідно накопичені природні напруження можуть індукуватися у землетруси за різкої зміни тиску рівня води. За 10 років оцінено сейсмічність регіону довкола Дністровського водосховища з огляду на дані рівня води у водосховищі, а також на зіставлення розміщення гіпоцентрів землетрусів на Державній геологічній карті кристалічного фундаменту. Окремо показано профіль цієї карти з проєктованими гіпоцентрами землетрусів, згідно з значна кількість гіпоцентрів землетрусів розміщується між різними літологічними структурами. Для оцінювання математичного взаємозв'язку між сейсмічністю та зміною рівня води у водосховищі виділено 111 періодів спуску чи наповнення водойми і обчислено сукупні параметри сейсмічної активності за ці періоди. Встановлено взаємозв'язок суми логарифмів енергії зі зміною об'єму води та поверхневого тиску в Дністровському водосховищі. З огляду на виведену лінійну залежність можна прогнозувати потенційну інтенсивність локальної сейсмічності, спричинену зміною рівня води в Дністровському водосховищі.

Ключові слова: сейсмічність, спричинена водоймами, зміни рівня води, Дністровський гідроенергокомплекс, Дністровське водосховище.