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INDUCED SEISMICITY DUE TO RESERVOIR IMPOUNDING: TWO TYPICAL EXAMPLES FROM THE PAMIRS

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Abstract: Comparison between induced seismicity due to the impounding of Lake Sarez caused by a natural landslide dam and to the impounding of Nurek man-made reservoir is presented. Both these cases show significant effects in seismic processes following the main impounding period. The differences in the character of induced seismicity in these two cases may stem from different levels of the natural state of stress and from different seismogeologic conditions.

Key words: induced seismicity, impounding of water reservoir, large earthquake, seismic regime.

1. GENERAL INFORMATION

Among the causes of induced earthquakes are the following principal kinds of the action of human activities on the Earth's crust:

(1) Withdrawal of media in solid and fluid phases from the interiors and removal of these to the surface.

(2) Penetration of fluids into rock masses.

(3) Large industrial explosions, including nuclear ones.

(4) Construction of large water reservoirs on the Earth's surface.

We are here concerned with induced earthquakes due to the last cause alone.

There have been many instances of large earthquakes, among them a few catastrophic ones, after and as a result of the impounding of large artificial water reservoirs (Rothe, 1970; Kissin, 1972; Simpson, 1976; Gupta, Rastogi, 1976; Nikolaev, 1977; Nikonov, 1977; Nouresku et al., 1979).

The principal empirical regularities of the origin of such earthquakes can be formulated as follows:

(1) Induced earthquakes occur in connection with the impounding of a few number of reservoirs (about 1/10 of the total number), apparently owing to increased natural seismic potential of the region, high crustal stresses, and particularly favourable geologic environment.

(2) Induced earthquakes can be excited when the water column in the reservoir is about 50 m, usually however for water depths of 100m or greater.

(3) The impounding of large water reservoirs affects the seismic regime and other seismicity parameters, not only in the area covered with water, but also over a larger area.

(4) Induced earthquakes can occur at distances of 10-15 km from the reservoir edge and after 5-15 years since the impounding .

(5) The number and intensity of shocks correlate with the rate of water loading (water level in the reservoir).

(6) Most induced earthquakes have low magnitudes and do not usually produce felt effects at the surface. However, shaking of intensity V has been recorded in several cases, while the highest recorded intensity was VIII-IX with M 6.3, Koyna, India in 1967 (Gupta, Rastogi, 1976).

We compare here earthquake occurrence during the impounding of a natural and an artificial reservoir in a highly seismic region as what Tadjikistan is (Fig. 1).

2. NATURAL CONDITIONS AND INDUCED SEISMICITY IN TWO LOCALITIES

It was in the Pamirs that a giant reservoir was impounded as a result of a naturally arising dam, a unique case during this century. Nature was as it were experimenting in rapidly making a great reservoir, an experiment that is outstanding as to scale and significance. For the comparison we used much better known data set for a relatively low-seismicity area in the Tadjik Depression where the large Nurek reservoir had been impounded on the Vakhsh River during the period 1960-1980 (Fig. 1).

2.1. Sarez Lake case.

The February 5, 1911 earthquake in the center of the Pamirs had magnitude M 7.4 and intensity IX (Fig. 1 and 2). It gave rise to a giant landslide of volume 2.2 km^3, which obstructed the Bartang River valley with a rock dam as high as 700 m and 7 km in width. Water began to accumulate rapidly behind this giant natural dam, the maximum height of the water column reaching 470 m after 12 years, by 1923.

(Fig. 3). The mean rate of water rise reached 40 m/yr during the first years. Later the level rose but slightly.

Evidence of the Pamirs earthquakes in the early 20th century is almost wholly noninstrumental, that is, in terms of intensity. There are no regular reports of earthquakes for the environs of Sarez. We constructed plots of recorded shocks with intensities III to VI for three main observation sites in the Pamirs having epicentral distances from Sarez in the range Δ = 130-150 km. Judging by the distribution of the shocks at Khorog site lying in the zone of intensity VI, the aftershock activity continued apparently for several years after 1911 (Fig. 4).

Three major local earthquakes (intensity VIII, VII-VIII, and IV) were recorded in the western environs of Lake Sarez (see Fig. 3), that is, near the location of the greatest water accumulation in the reservoir following the period of aftershock activity and during 20 years after the termination of the fast water level rise. Shocks of this size have not been recorded subsequently, during 50 years there.

Some evidence is available in favour to consider these events as being due to the impounding of the reservoir. The evidence is as follows:

(1) Occurrence after the aftershock period and nonoccurrence subsequently when the water level did not vary. (2) The first, largest shock of intensity VIII was strictly timed to occur at the termination of the period of rapid water level rise. (3) The earthquakes occurred near the highest-load, head part of the reservoir.

If our identification of these earthquakes as belonging to induced seismicity is true, then this is an example of large seismic events induced by the impounding of a large natural reservoir.

2.2. Nurek reservoir case

Let us compare this example with the closest-lying artificial reservoir, the Nurek one, in the low mountains of western Tadjikistan.

The Nurek reservoir is situated in the relatively low-seismicity area of the Tadjik Depression on the Vakhsh River (see Fig. 1). Fifteen seismic stations have been operated there since 1965, providing a complete reporting of $M \geq 1.5$ events (Induced..., 1975; Mirzoev et al., 1987). Seventeen years before the impounding the largest earthquakes occurring there had magnitudes M 5.2 at 10-15 km depth.

The distribution of relatively large shocks during this period is shown in Fig. 5. The earthquakes are seen to tend to occur along the main faults away from the future reservoir. However, during the period after the start of the fast impounding (1972-1985) the epicenters were mainly located around the deepest, head part of the reservoir (see Fig. 5).

The mean number of small earthquakes after the start of the impounding became twice as great, but the number of relatively large ($M \geq 4.5$) shocks significantly decreased (Fig. 6). The b-value also decreased (Table 1). Accordingly, the total release of seismic energy decreased (by a factor of three) and became more uniform over time.

The relation of observed seismicity changes with the action of the reservoir can be seen, not only for the periods before and after the impounding (in 1972), but also within the latter. The main increases in seismic activity occur at the ends of short periods of rapid impounding in 1972, 1976, 1980, 1984.

The authors of a study (Mirzoev et al., 1987) relate the observed facts to decreased friction coefficient on slip planes in rocks due to lubrication by water rather than to increased loading in the reservoir. In their opinion, the earthquake hazard in the reservoir area has decreased. The conclusion may be true for an area where plastic rock sequences widely occur, as is the case for the Nurek area.

3. COMPARISON BETWEEN TWO CASES OF INDUCED SEISMICITY

The seismic consequences due to the impounding of the two reservoirs are strongly different, as we have just seen.

In the Pamirs, the excitation manifested itself in isolated large earthquakes with M_{max} up to about 5.6, although an increase in small magnitude seismicity is not ruled out.

In the Tadjik Depression, the impounding of the reservoir produced seismic activation at the level of small shocks with M_{max} 4.5 with an overall decrease of released energy, because moderate magnitude earthquakes became fewer, while large ones did not occur at all (see Fig. 6, Table 1).

To gain an understanding of this distinction, let us compare again the principal similarities and differences in the impounding of the two reservoirs (Fig. 7, Table 2). Both reservoirs, the natural and the man-made one, were impounded during roughly equal time periods (10 ± 2 years) and at roughly equal rates (35 ± 5 m/yr).

Owing to different volumes of accumulated water masses, the specific load at Sarez was 4 times as high, namely, 20 kg/cm^2 as compared with 5 kg/cm^2 at Nurek.

The controlling factor seems to have been different. Firstly, the

Pamirs is a highly seismic region having a high seismic potential, while the Tadjik Depression (in the Nurek area) belongs to regions of moderate seismicity.

The second cardinal difference is that Lake Sarez originated in the zone of a deep-seated seismogenic fault separating rigid consolidated blocks of the Paleozoic basement capable of storing elastic energy and subject to brittle failure. In contrast to this, the Nurek reservoir was made in strongly dislocated and fragmented plastic rock sequences of Mesozoic and Cenozoic time mostly subject to plastic deformation.

4. CONCLUSION

Two above mentioned factors, the primary differences in the level of tectonic stresses and seismicity and the differences in physical and mechanical rock properties of the basement, which in our opinion produced the cardinal differences in induced seismicity for the two cases. It did not matter whether the impounding was natural or artificial.

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Table 1. Comparison between seismic characteristics before and after beginning of the Nurek reservoir impounding

Characteristics	Before		After	
I. Duration of observational period,yr	II		I4	
2. Everage number of shocks per month	9	$\sigma = 0,45$	20	$\sigma = I,I$
3. Inclination of reccurence graph, γ	- 0,4I		- 0,53	
4. Number of relative strong shocks (K=12 and K= 13 are class of energy)	$K_{I3} = 4$; $K_{I2} = 6$		$K_{I2} = 6$	
5. Maximal magnitude of shock,M	5,2		4,5	

Table 2. Comparison between parameters of reservoirs and induced seismicity

Reservoir parameters							Seismicity	
Name of reservoir and location	Period of impounding,yr	Dam hight, m	Maximum water column, m	Maximum capacity, km^3	Rate of impounding, m/yr	Main calculated load, kg/cm^2	Magnitude of maximal shock	Number of registered shocks
Sarez , Pamir highland	I9II-I923:I2	750	500	I7-I8	40	I9-20	6	3
Nurek, Tadjik depression	I972-I980:8	3I0	270	I0,5	30	4-5	4,5	23

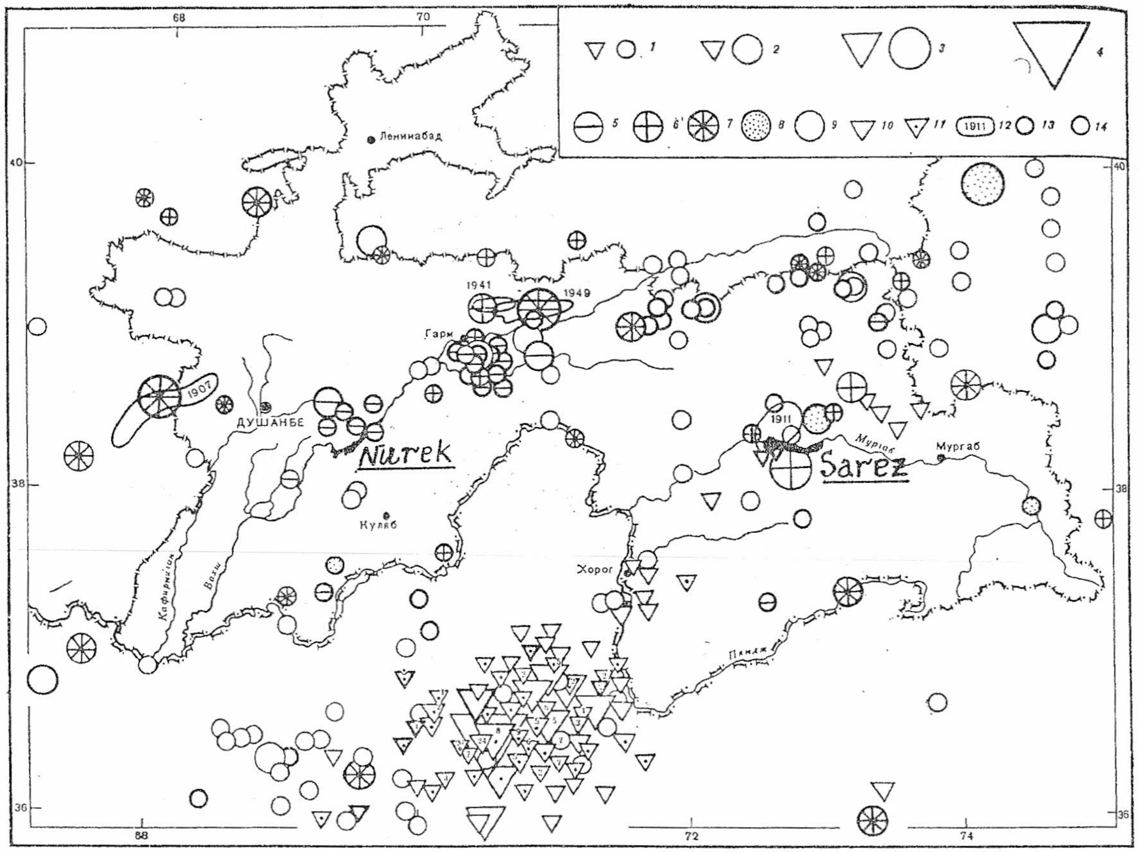

Fig. 1. Epicentres of strong earthquakes in Tadjikistan,1895-1973 and the reservoirs location. 1 - 4 -magnitudes: 1 - 5.0-5.9; 2 - 6.0-6.9; 3 - 7.0-7.9;4 - 8.0-8.9; 5 - 11 - depth,km : 5 - 0-I0; 6 - 11-20; 7 - 21-40; 8 - 41-70; 9 - 0-70; 10 - 80-150; 11 - 150-300. 12-isoseismals of the earthquakes with intensity 9 and years of their occurence. 13 -14 - location accuracy : 13 classes A and B; 14 - class C.

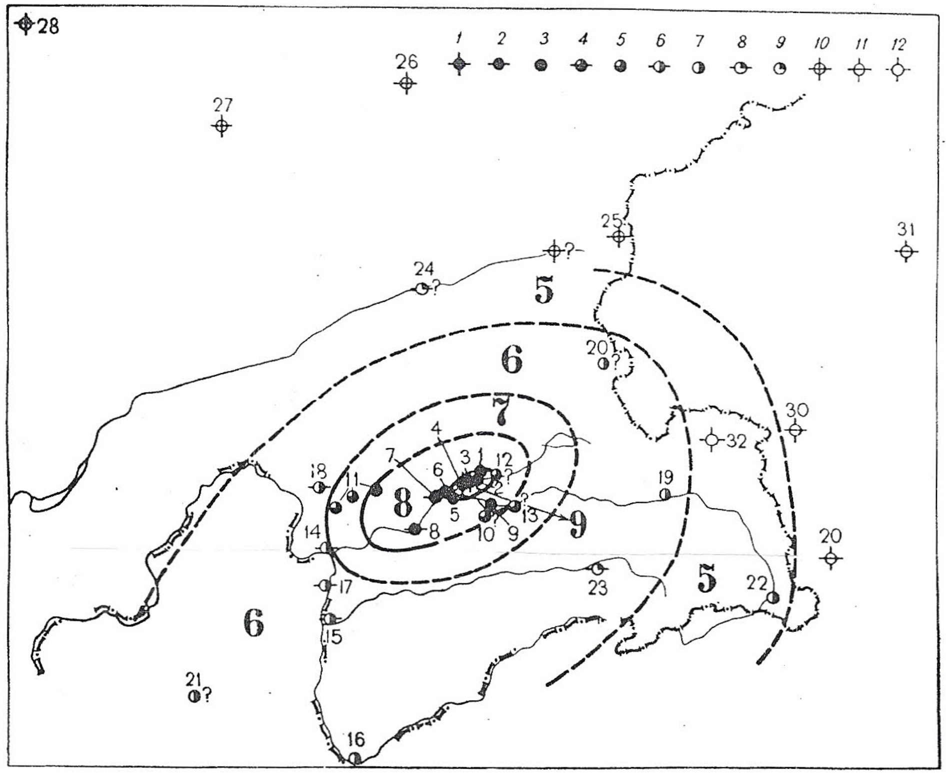

Fig. 2. Map of isoseismals of the Sarez,1911, earthquake in the Pamir. Compiled by the author. Intensity in the MSK-64 scale : **1** - 9; 2 - 8-9; 3 - 8 ; 4 - 7-8; 5 - 7; 6 - 6-7;7 - 6; 8 - 5-6; 9 - 5; 10 - 4-5; 11- 4; 12 - 3-4.

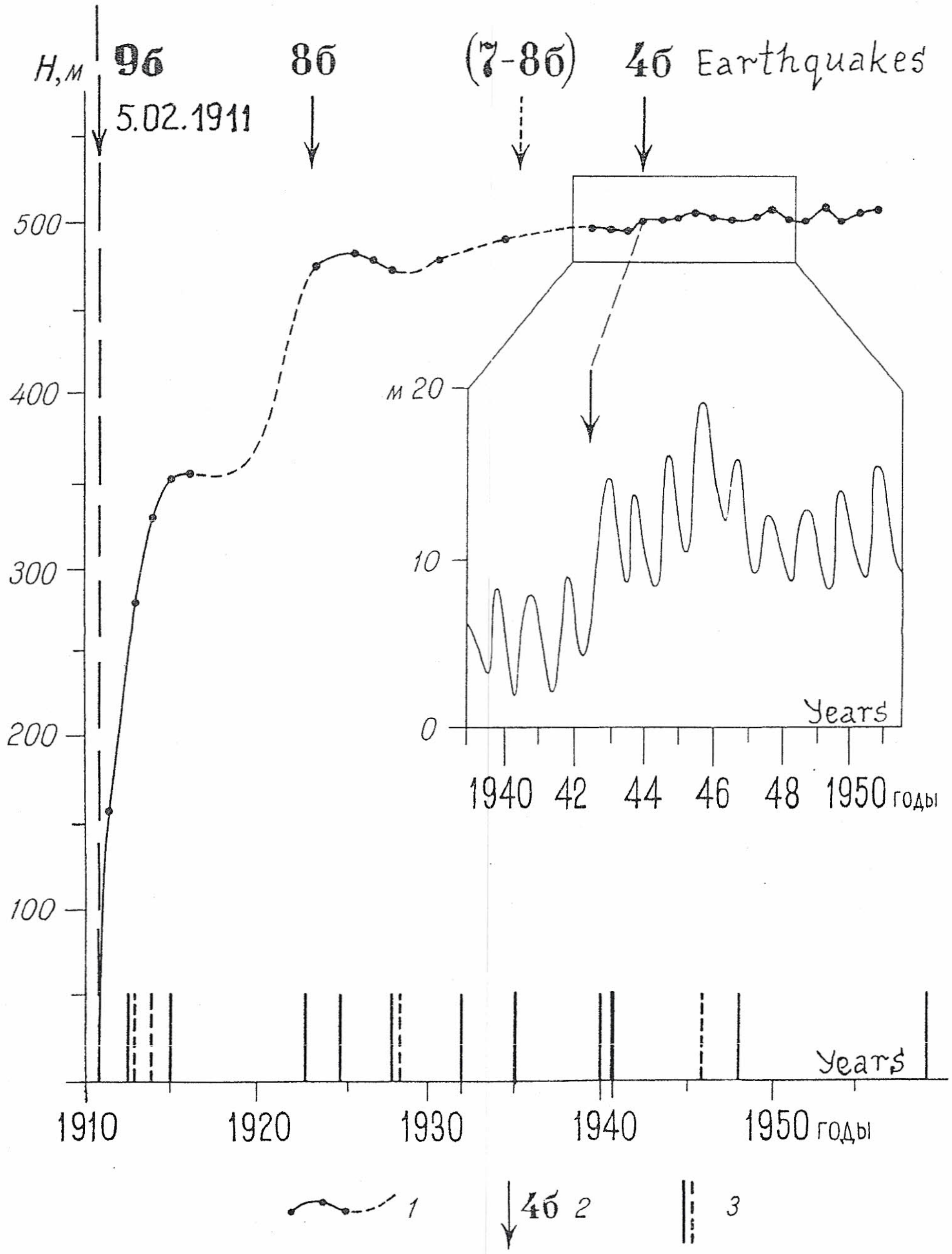

Fig. 3. Rising of the water level due to the Sarez lake impounding after the eathquake of 1911 and apparently indused seismic events in the reservoir vicinity. Compiled by the author.

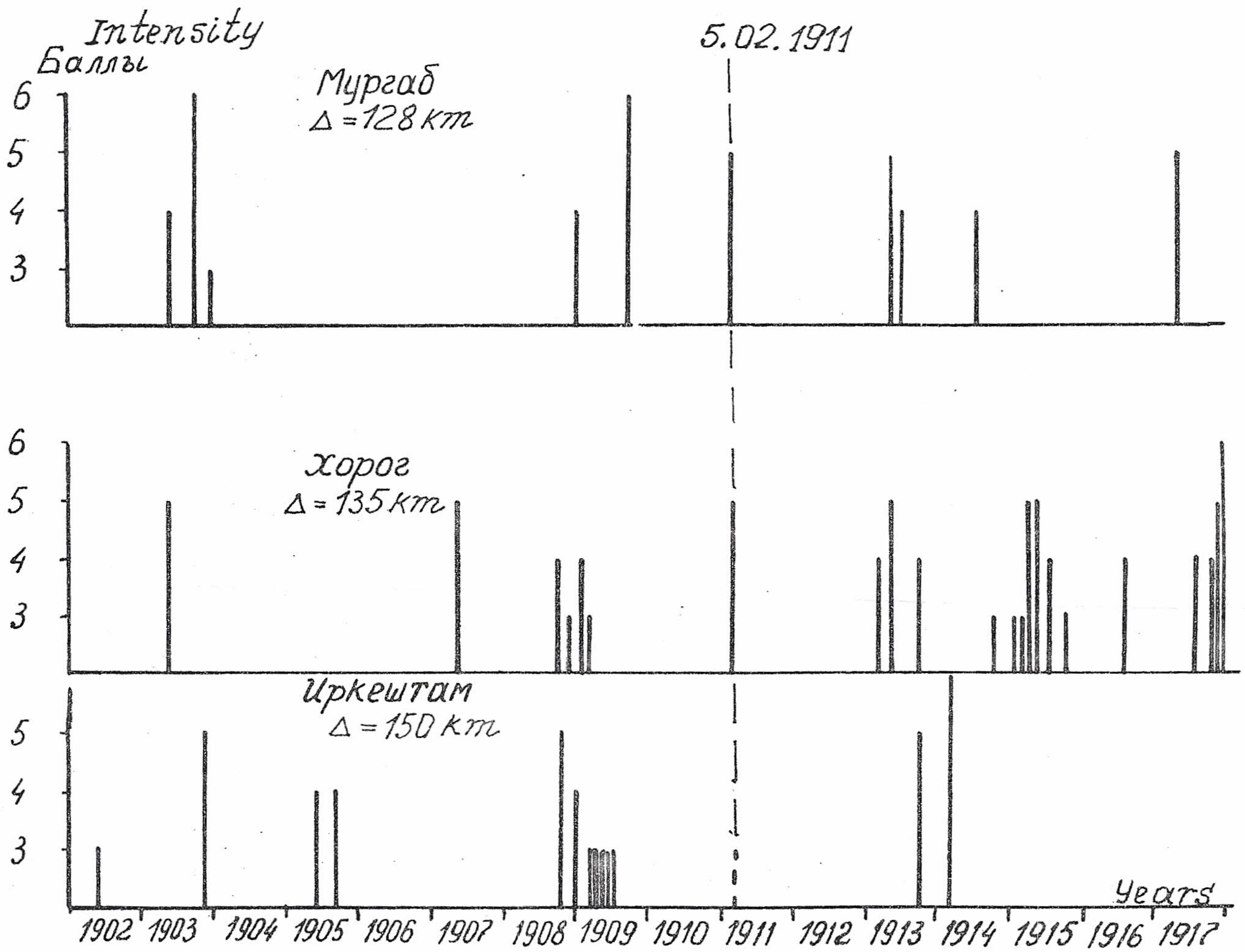

Fig. 4. Allocation in time of notable eathquakes within the Pamirs before and after the Sarez, M 7.4, earthquake of 1911. Compiled by the author.

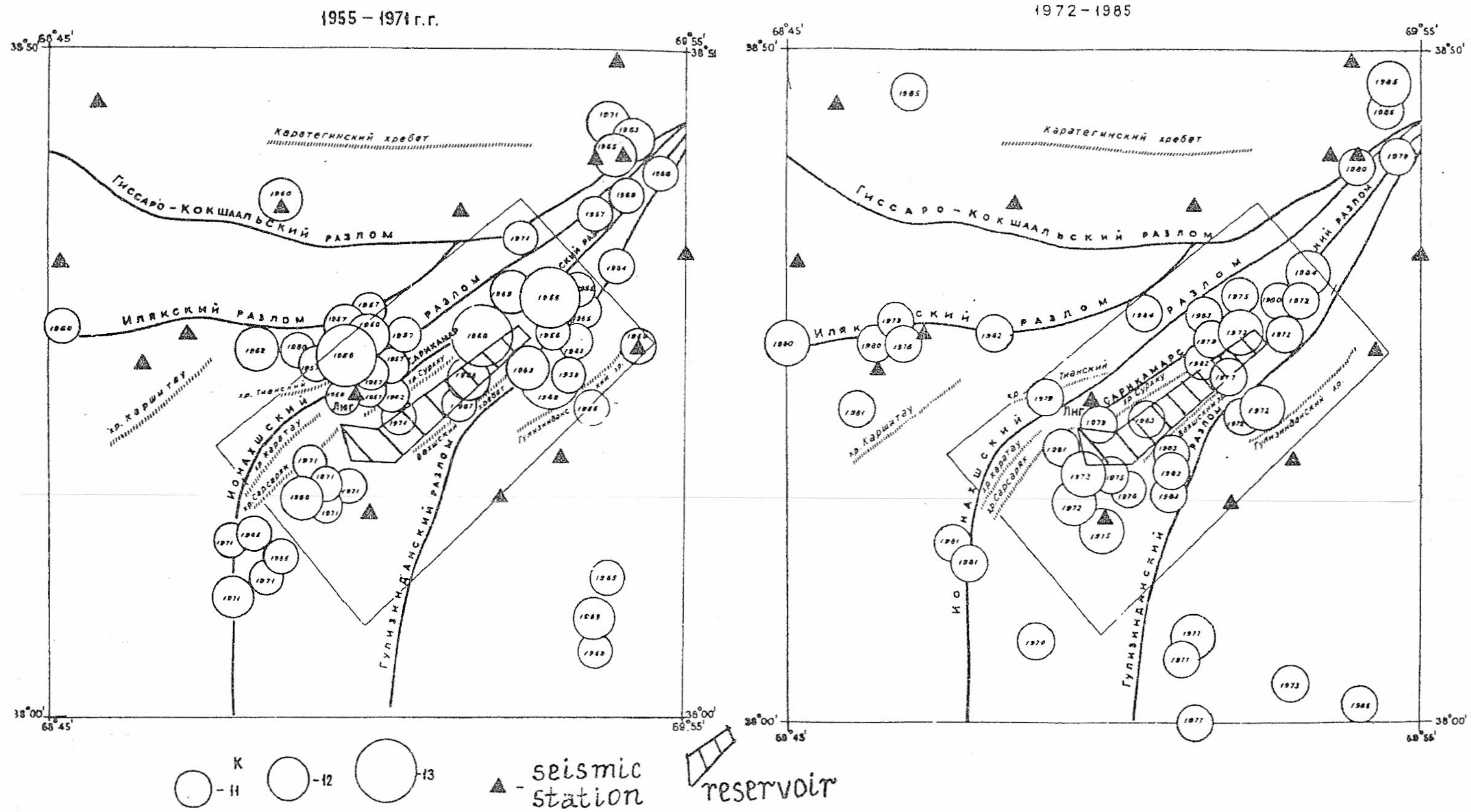

Fig. 5. Maps of earthquake epicentres, Nurek reservoir area. After Mirzoev et al., 1987. Classes of energy - 11, 12, 13.

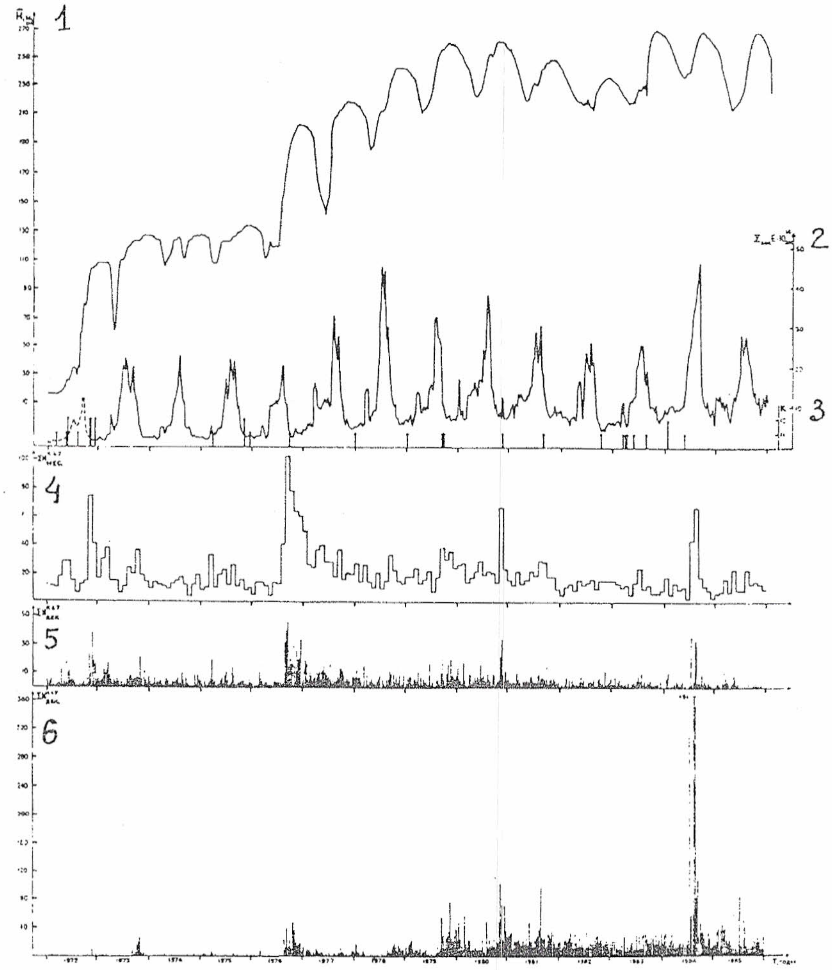

Fig. 6. Water level changes and seismicity, Nurek reservoir,1972 -1975 (Mirzoev et al.,1987).

1 - water level curve, m . 2 - decadal sum of water current energy in the tunnel output $\sum E_{dec}$. 3 - earthquakes, energy classes 11,12 . 4 - number of earthquakes, K 7, for a month, $\sum N^{k \geqslant 7}$. 5 - number of earthquakes, $K \geqslant 7$, for a decade. 6 - the same, $K \leq 7$.

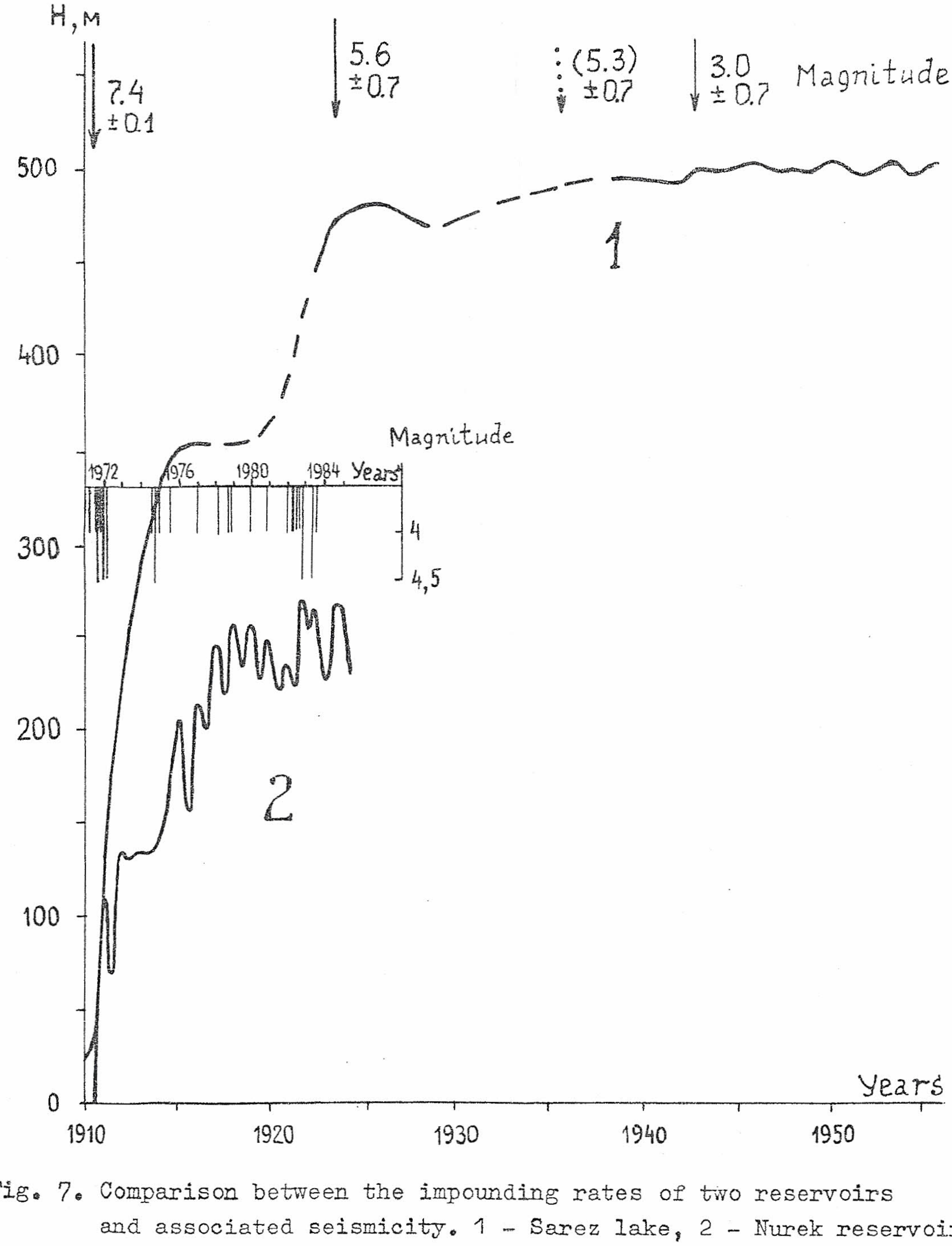

Fig. 7. Comparison between the impounding rates of two reservoirs and associated seismicity. 1 – Sarez lake, 2 – Nurek reservoir