Nonlinear Dynamics of seismicity and fault zone strain around large dam: the case of Enguri dam, Caucasus.

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Abstract

The 271 m high Enguri arch dam, still one of the highest arch dam in operation in the world, was built in the canyon of the Enguri river (West Georgia) in the 1970s. It is located in a zone of high seismicity (MSK intensity IX) and close to the Ingirishi active fault. The high seismic and geodynamical activities together with the large number of people living downstream of the dam made the Enguri dam a potential source of a major catastrophe in Georgia. Thus, the Enguri Dam with its 1 billion cubic meters water reservoir should be under permanent monitoring. At the same time this area is an amazing natural laboratory, where one can investigate both tectonic and geotechnical strains/processes and their response to the lake load-unload impact, i.e. the reaction to a controllable loading of Earth crust. This is an important scientific issue, connected with a fundamental problem of Reservoir Induces Earthquakes as well as with environmental geotechnical problems, related to the safety of large dam. Application of nonlinear dynamics methods allows dividing events, ordered by reservoir water regular strain impact from the background seismicity.

1. Introduction.

Monitoring of strains and seismic activity in the area of large dam is a unique tool for understanding the intimate connections between earthquakes generation and man-made regular quasi-periodic strains in the Earth, created by seasonal water load-unload in the reservoir. We can consider large dams' area as a natural laboratory, providing possibility of studying seismic process in almost controlled (repeated) conditions.

The 271 m high Enguri arc dam (still one of the largest in the world) was built in the canyon of Enguri river in West Georgia. It is located close to the Ingirishi active fault system, in a zone of high seismicity, MSK intensity IX. The volume of the lake at Enguri dam is 10^9 cubic meters and the water level high in the lake varies seasonally by 100 m, which means that Enguri reservoir can activate Reservoir-Triggered Seismicity (RTS). The dominant tectonic feature of the region is the active East-West oriented Ingirishi fault, located to the north of the dam: its branch fault crosses the foundation of the Enguri dam (Chelidze et al, 2013).

Taking into account high potential danger of the object, geophysical monitoring system was organized even before construction works for providing secure exploitation of the large Enguri dam. Due to a high seismic activity of the region, the seismic station's network was installed in the area of Enguri dam also well before its construction with the aim of studying possible reservoir-triggered activity (Balavadze, 1981). The monitoring system of Enguri Dam and its foundation includes network of tiltmeters, piezometers and reverse plumblines in the dam body (Chelidze, 2013), meteo-station, water level gauge for monitoring water level in the lake, as well as complex of strainmeter and tiltmeters, installed in the dam body and its foundation (Abashidze, 2001).

The problem of human-induced earthquakes, including RTS, became quite actual last decades (Grigoli et al, 2017; Foulger et al, 2017; Savage et al, 2017). The RTS pattern in the Enguri area should depend on the Water Level (WL) variation regime in the lake (Gupta, 1992; Gupta, 2018). The main goal of the paper is to apply new methods of complexity analysis in order to assess in a quantitative way the correlation between WL variations and local seismicity and define the scale of man-made activity on the local (natural) seismicity pattern.

2. Data.

The branch fault of the main Ingirishi fault crosses the foundation of Enguri dam and thus, poses hazard to its safety. In order to monitor permanently the fault behavior, two years before the first filling of the reservoir, in December 1974, the quartz strainmeter, crossing the fault zone (FZ) was installed in the adit, located 100 m downstream from the foundation of the dam. The strainmeter's fixed and free parts are located on the intact rocks on the opposite sides of the FZ and are separated from this 10 m-wide zone by the 5 m distance (the full length of the quartz tube is 22.5 m). This means that the device records displacement of the intact blocks, divided by the fault zone in the normal to the fault plane direction, so it shows fault zone's extension/contraction. The free end of the tube is equipped with photo-optical recording system (Abashidze, 2001). The displacements' sensitivity of this system is of the order of 0.18 μm/mm, which allows also to record a tidal component of the fault zone strain. At present, the laser system (Laser model R-39568, Green HeNe Laser, 633 nm and Laser Position Sensor OBP-A-9L) doubles the photo-optical registration. The laser is attached to the free end of the same quartz tube. Sensitivity of the strainmeter with the laser sensor is one μm/mm.

The earthquake time series (ETS) for Enguri area from 3 January 1974 to 31 December 2016 was compiled using catalogs of Institute of Geophysics and International Seismological Centre. Our study area includes events located on the distance 50 or 100 km from the lake. The completeness magnitude (CM) for the whole used catalog is around M 1.7 (Fig. 1), but in some cases we confine ourselves by magnitude 2.2 for confidence, as in some periods the CM value increased to M2.2 due to non-stable functioning of national seismic network.

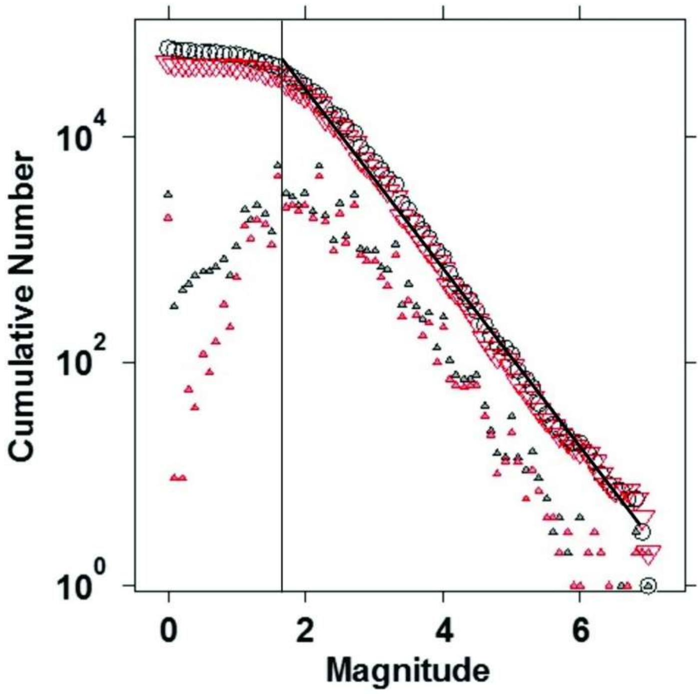


Fig. 1. Cumulative Gutenberg-Richter plot of the whole (black circles) and aftershock-depleted (downward red triangles) catalogue of Georgia. The plot shows also the binned frequency-magnitude distribution of the whole (upward black triangles) and aftershock-depleted (upward red triangles) catalogues. The completeness magnitude is around M1.7.

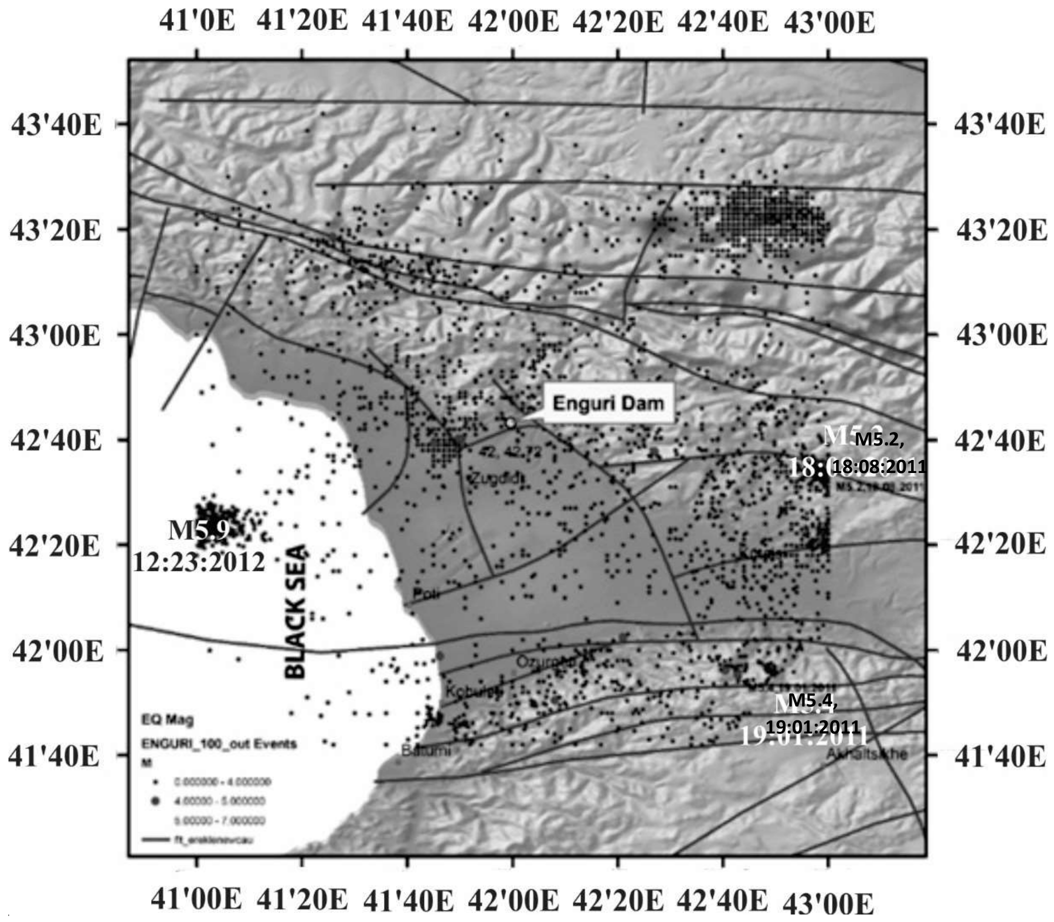


Fig. 2. Seismicity of the Enguri Dam region within 100 km distance with the scheme of active tectonic faults, according to (Gamkrelidze et al, 1998).

In Fig. 2 we present a spatial distribution of seismicity in the Enguri Dam region within 100 km distance from the dam as well as the scheme of active tectonic faults, according to (Gamkrelidze et al, 1998).

Fig. 3 shows almost 40-years' history of the crossing the dam foundation fault zone extension - FZE - beginning from 1974 (i.e. FZE is variation of the normal to the fault plane displacement of the free end of the strainmeter) and water level (WL) change in the Enguri reservoir *H* beginning from April 1978. According to Fig 3 the dam area experiences stresses of different origin, acting on the different time scales, from decades to months and days. Actually, the object under study is a natural large-scale laboratory for investigation of geotectonic, man-made and environmental impacts on the fault zone deformation. The summary contributions of these processes are reflected in the time series of fault zone strain. It is evident that the fault dynamics reflects joint influence of two main factors: one leads to piecewise linear (in time) displacement (trend component) and the other one – to quasiperiodic oscillations, decorating the main trend.

The long-term piecewise-linear trend documents persistent separation of fault faces (Fig. 3), extending to 7000 μm (7 mm) during observation period. The FZE rate (y) depends on the time (t) following a simple linear equation: $y(t) = at - b$. where the coefficient a, the slope of the linear component of the FZE or the strain rate, differs from one period to another (Table 1). As the trend component with the same strain rate was recorded even before dam construction and lake filling, we attribute it to the long-term regional tectonic stress action.

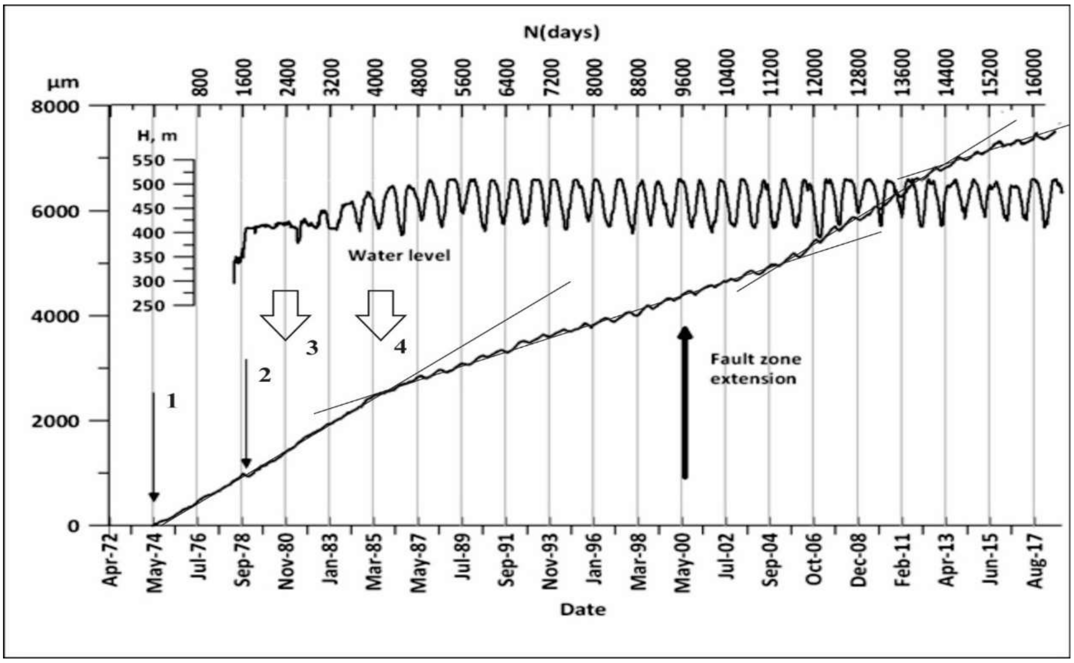


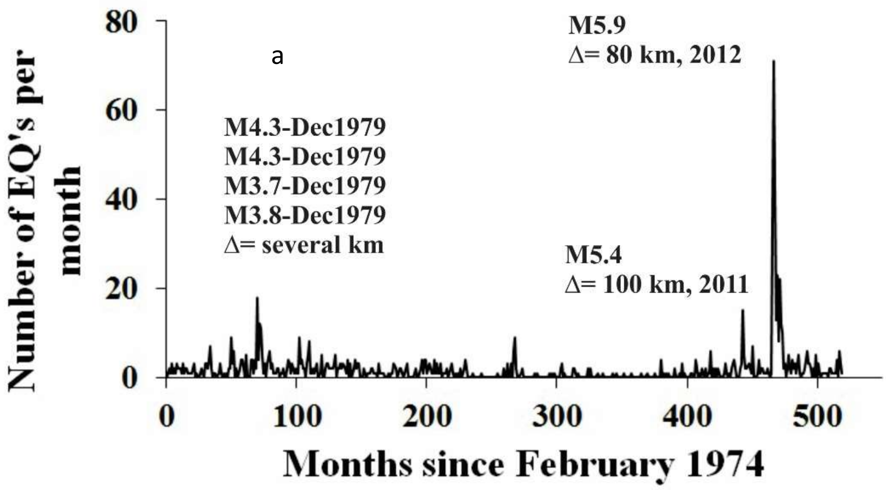
Fig. 3. WL in the Enguri lake from 1978 (upper curve) to 2017 and the data on the extension/compaction of the branch of a large Ingirishi fault, crossing the foundation of the dam from 1974 to 2017 (lower curve). Arrow 1 corresponds to the start (in 1974) of strainmeter monitoring 4 years before impounding, arrow 2 – to the episode of the fault compaction by approximately 90 μm due to WL fast rising by 100 m in 1978, arrows 3 and 4 show the moments of transitions in the nonlinear dynamics pattern of local seismicity (see section 4). Upper horizontal axis shows number of days after start of strainmeter monitoring. Dashed straight lines mark periods of fault's constant extension component slope.

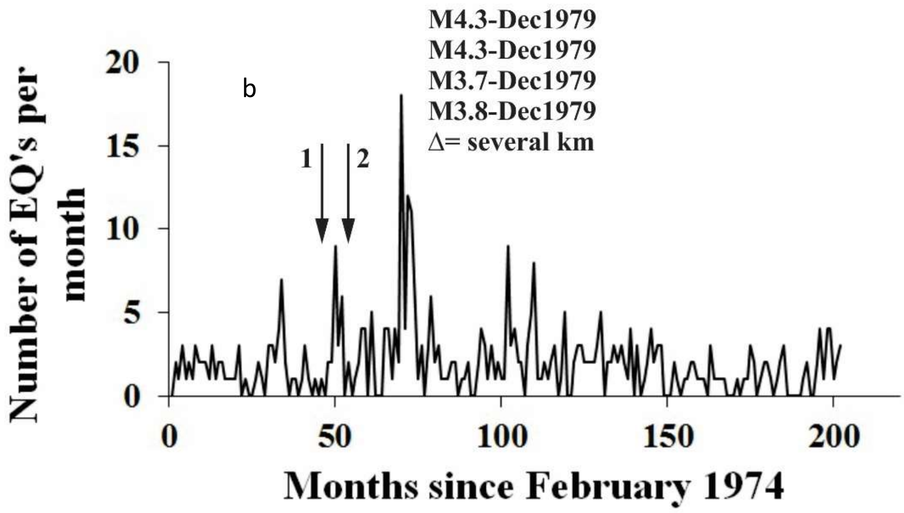
At the same time, the fault zone extension rate (FZER) changes significantly with time, reflecting action of some non-stationary factors. In the Table 1 we show the periodization of FZE behavior following the pattern of data evolution according to Fig. 3, taking into consideration both components of strain – tectonic and anthropogenic.

Table 1. Periodization of the fault zone extension

Number of periods	Periods	Number of days in the period; in brackets the same from the zero day (May 1974) to the end of the given period	Tectonic component of strain rate *a* microns/year	Pattern of lake impounding regime (man-made component of strain)
1	May1974–Jun 1978	1500 (1500)	250	Before lake impounding
2	Apr1978 –Jan 1981	1300 (2800)	235	WL in the lake raised to 100 m
3	Jan1981–May 1985	1400 (4200)	235	Irregular quasi-periodic regime
4	May 1985-Sep 2004	7000 (11200)	160	Regular quasi-periodic regime
5	Sep 2004–Feb 2013	3200 (14400)	230	Regular quasi-periodic regime
6	Feb 2013-Mar2018	2000 (16400)	150	Regular quasi-periodic regime

The most probable source of quasiperiodic changes in the FZE dynamics in Enguri area is the variation of the water load in the lake. We elucidate six periods with appreciable differences in the WL regime: i. May1974–Jun 1978, period before water fill, which we consider as a reference; ii. Apr1978–Jan 1981 is the period of the initial filling of reservoir; iii. Jan1981–May 1985 is the interval of initial irregular (quasiperiodic) variation of WL; iv. May 1985- Sep2004, in this period we observe regular quasi-periodic load-unload regime, though tectonic component of the strain rate varied in this period from 235 to 160 microns/year; v. during Sep 2004–Feb 2013 there is a regular quasi-periodic regime, but the tectonic component of the strain rate returns to the value 230 microns/year; vi. in the interval Feb 2013-Mar2018 a quasi-periodic component is decorating the tectonic strain rate of 150 microns/year.





b.

Fig. 4 a, b. Number of EQs (M≥ 2.2) per month versus month number in the radius 100 km from the dam, Δ is the distance of from the epicenter of a given EQ to the dam: (a) since February 1974 till 2017; (b) since February 1974 till 1991. Arrow marks 1 and 2 in Fig. 4 b correspond to: (1) beginning of filling and (2) -WL rising to 100 m high.

General Characteristics of the test area seismicity. In Fig. 4a we show the earthquake number per month from 1974 till 2017 and in Fig 4 (b) - the same on the extended time scale: since February 1976 till 1991 within 100 km distance from the dam. We also mark the magnitudes M and EQ's separation from the dam Δ for the strongest events. According to Fig. 5 b the strong seismic activity very close to the dam (Δ several km) in December 1979 with 4 events of magnitude M3.7-M4.3 follows the fast initial recharge of the lake to the critical for RTS initiation water level (100 m) in September 1978, i.e. with a lag 14 months.

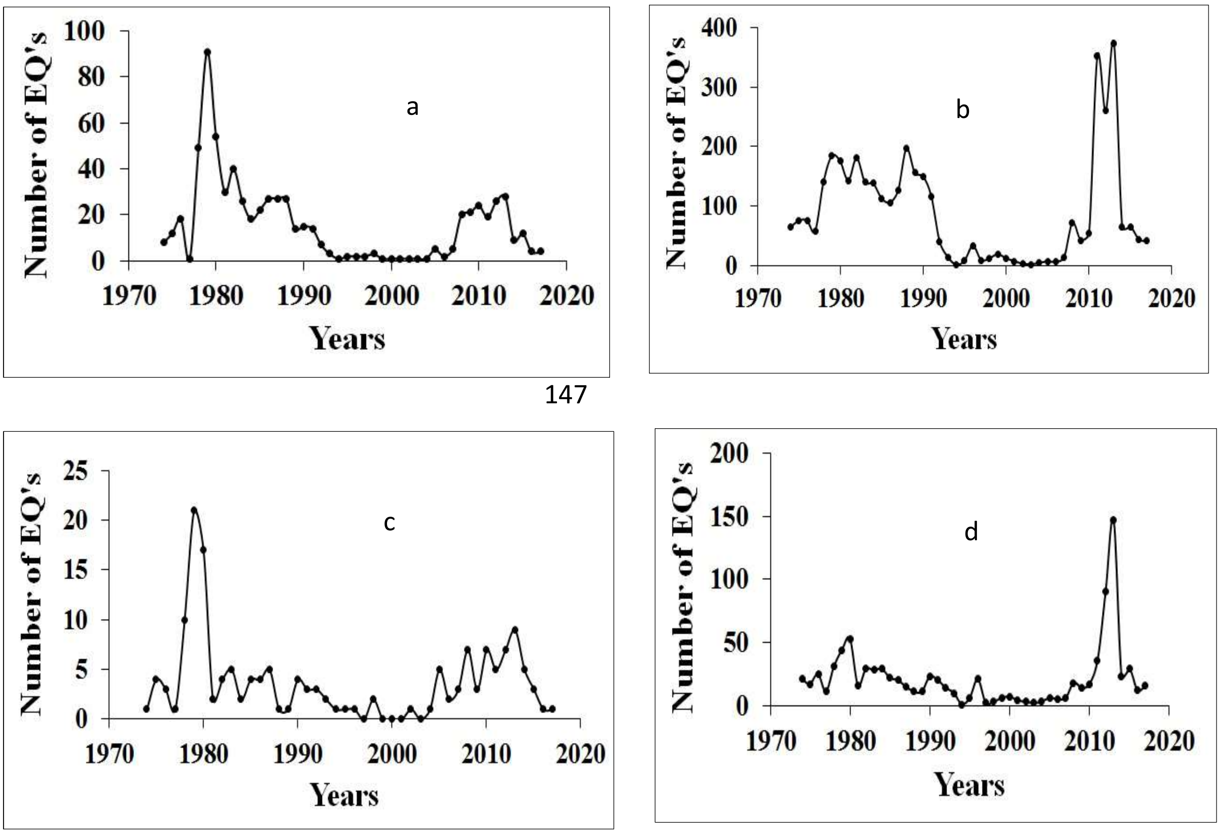


Fig. 5. EQ number versus time in the near and larger zone: (a) EQ number - all events, including M<2.2 in the near zone, R=50 km; (b) EQ number - all events, including M<2.2 in the large zone, R=100 km; (c) EQ number – events with M>2.2 in the near zone, R=50 km; (d) EQ number – events with M>2.2 in the large zone, R=100 km.

Fig 4 a presents the number of events per month in the area with radiuses 50 and 100 km around Enguri dam, where several relatively strong EQs occur from 1974 to 2017. The epicenters of EQs M4.3 (21 Dec1979), 4.3 (27 Dec 1979) are close to the Enguri lake and the EQs M5.4 (19 Jan 2011), M5.9 (23 Dec2012) shown in the Fig. 2a, lay on the distance 80-100 km.

To separate out more clearly the man-made impact, we present on the Fig. 5 b the detailed seismic rate during first 200 months after January 1974. The corresponding water level regime we present in Fig. 3: the recharge began in April 1978 (arrow 1) and WL was abruptly risen to 100 m in November 1978 (arrow 2). Almost simultaneously the abrupt compaction of the fault zone crossing the foundation of dam by approximately 90 μm was registered by the strainmeter, installed on the fault (Fig. 3). Almost the year later, in December 1979, series of EQs of magnitudes from 3.7 to 4.3 occur close to the reservoir. These effects follow (with an year lag) the time of WL rising to the critical high of 100 m, when, according to existing data (Foulger, 2017; Gupta, 1992, 2018) the water load can generate Reservoir Triggered Seismicity (RTS).

In order to better resolve the seismic events related to filling and exploitation of the dam reservoir we used cellular approach (Kafka, John, 2011), namely, we plotted separately the time sequences of all registered EQs (all EQs of magnitudes M>1) in the near to dam zone, in the radius R=50 km from the dam and in the larger area, in the radius R=100 km (Fig. 5 b). In Figs 5 c, d we show the same data for the EQs of magnitudes M≥2.2. Considering Fig 5 we can conclude that the EQ statistics in the near zone R=50 km (Figs 5 a, c) is dominated by events connected with reservoir impoundment and the swarm of EQs with Δ of the order of several km (compare with Fig. 4b), when the most part of seismic activity in the larger zone R=100 km (Figs 5 b, d) is due to the relatively strong remote events of magnitude M5.2-5.9 with Δ of the order of 80-100 km, which are too far from Enguri dam and belong to the class of regional tectonic events (see Figs. 2, 3b). It follows that in order to distinguish RIS events it is better to analyze seismic catalog in the near zone (R=50 km), where dominate seismic events, located close to Enguri dam. This restriction does not work for analysis of complexity, especially when we analyze waiting times of EQ, because RIS is characterized by quasiperiodic recurrence property due to regularity of reservoir load-unload. In turn it means that the role of random seismic events when studying regularity in waiting times even at the distance 100 km is relatively small.

3. Methodology.

The earthquake time series (ETS) presented in Fig. 5 a, b present a complex mix of background seismicity, characteristic for the seismotectonics of the test area with a seismic response to the lake impoundment and further – to WL quasiperiodic regulation. To single out the dynamical patterns of the seismic data sets connected with WL variation, we used new effective methods of complexity analysis (Chelidze, Valliantos, Telesca, Eds., 2018) applied to magnitudes and waiting times of earthquake time series (ETS). The complexity analysis allow recognition of periods with different level of ordering/determinism, which we connect with transition in WL regime from disordered (1978-1984) to more ordered (1985-1986) and finally, to quasi-periodic loading (1986-untill now). We give short description of these methods below.

Earlier several studies were devoted to complexity analysis of seismic regime in the Enguri dam area, namely to variation of the phase diffusion coefficient of phase differences between daily released seismic energy and water level daily variations (Matcharashvili et al, 2008; 2010), Visibility Graph Analysis (Telesca, Chelidze, 2018) of Singular Spectrum Analysis (Telesca et al, 2012). In the present paper we analyze recurrent patterns of local seismicity, using such methods as Recurrence Plots, Detrended Fluctuation Analysis and Lempel and Ziv complexity measure.

Recurrence Plots (RP) Recurrence Plots allow visualization of recurrent behavior of dynamical system by plotting the arbitrary close (after some time lag) states in the two-dimensional projection of the high-dimensional phase space trajectory (Eckmann et al, 1987; Webber and Marwan, 2015). The recurrence of the same state after some time lag is plotted on the square matrix, where both axes represent time, by zeros and ones or by differently colored dots. The time lag between recurrent points i and j of the trajectory is defined as the threshold time interval (threshold distance) ε_i. The RP revealed some structural patterns, which are different for different degrees of determinism in the phase space of the system.

Detrended Fluctuation Analysis (DFA). Long-range time-correlations in the investigated data sets were assessed by the method of Detrended Fluctuation Analysys (DFA) [Peng et al, 1994, 1995]. Method of DFA permits the detection of long-range correlations embedded in a nonstationary time series through calculation of a quantitative parameter - DFA scaling exponent. This analysis technique is widely accepted and often used for different types of time series including geophysical data sets [e.g. Eichner, et al. 2003; Telesca, et al. 2004, 2007; Matcharashvii et al. 2012, 2015].

The basics of DFA are well known and described in series of often cited articles, so we will just briefly stop on its main steps. At first given time series of N samples is integrated. After, the integrated time series is divided into boxes of length n, and in each box the polynomial local trend is calculated and removed. Then N/n mean squared residuals - Detrended Fluctuation Functions ($F(n)$), should be calculated for each box of size n.

$$F(n) = \sqrt{\frac{1}{N}\sum_{i=1}^{N}\left[Y(i) - Y_n(i)\right]^2} \,.$$

Since $F(n)$ increases with the box size n, in case of fractal or self-similar properties of analyzed data, a power-law behavior $F(n) \sim n^{\alpha}$ can be revealed. If a power law scaling exists, the $F(n)$ vs. n

relationship, in double logarithmic fluctuation plot, will be linear or close to be linear and the scaling exponent α can be estimated. If the scaling exponent $\alpha = 0.5$, we deal with the uncorrelated dynamics of random walk type [Peng et al. 1994; Liu et al 1999]. In this case, the time series is identical to white noise. If α is different from 0.5, then the time series is regarded as long-range correlated or anticorrelated, with $\alpha > 0.5$ or $\alpha < 0.5$ accordingly [Peng et al. 1994, 1995; Bahar et al 2001]**.** The scaling exponent α is considered as an indicator of the nature of the fluctuations giving the information about the long-range power law correlation properties in the analyzed data sets. DFA can be accomplished for different order of the polynomial fitting in order to eliminate trends of certain origin.

Recurrent quantification analysis. In order to further quantify changes in dynamical structure of analyzed data sets, we have used recurrence quantification analysis approach (Zbilut and Webber, 1992; Webber and Zbilut, 1994; et al., 2007; Webber and Marwan, 2015). In general RQA is a quantitative extension of Recurrent Plot (RP) construction method which is based on the fact that returns (recurrence) to the certain system condition or state space location is a fundamental property of any dynamical system with quantifiable extent of determinism in underlying laws (Eckman et al., 1987). In order RQA calculations to be successfully fulfilled, at first the phase space trajectory should be reconstructed from the given scalar data sets, the proximity of points of the phase trajectory should be tested and marked by the condition that the distance between them is less than a specified threshold (Eckman et al., 1987). In this way, a two-dimensional representation of the recurrence features of dynamics embedded in high-dimensional phase space can be obtained. Then small-scale structure of recurrence plots can be quantified (Zbilut and Webber, 1992; Webber and Zbilut, 1994; Webber and Zbilut, 2005; Marwan et al., 2007; Webber et al., 2009). RQA technique quantifies visual features in a $N \times N$ distance matrix recurrence plot and defines several measures of complexity. Exactly, RQA provides several measures of complexity based on the quantification of diagonally and vertically oriented lines in the recurrence plot. In this research, we present one of such measures (%Determinism), which often is used to reveal changes in the extent of regularity in analyzed data sets.

Lempel and Ziv complexity measure. Lempel and Ziv algorithmic complexity (LZC) calculation (Lempel & Ziv, 1976; Aboy et al. 2006; Hu and Gao, 2006) is another often used method for quantification of the extent of order in analyzed data sets of different origin. LZC is based on the transformation of given data sequence into new symbolic sequence. For this original data are converted into a (0, 1) sequence by comparing them to a certain threshold value (usually median of the original data set). Once the symbolic sequence is obtained, it is parsed to obtain distinct words, and the words are encoded. Denoting the length of the encoded sequence for those words, the LZ complexity can be defined as

$$C_{LZ} = \frac{L(n)}{n}$$

where *L(n)* is the length of the encoded sequence and *n* is the total length of sequence (Hu&Gao, 2006). Parsing methods can be different (Cover & Thomas, 1991; Hu and Gao, 2006). In this work we used scheme described in Hu and Gao (2006). Data sequences with a certain regularity are less complex, and the LZ complexity increases as the sequence grows in length and irregularity. In our case the sequence length is constant and LZC depends only on the level of regularity.

4. Results

Results of Complexity analysis. In this study, we analyzed two types of ETS related to the seismicity of Enguri area: the waiting times' and the magnitude sequences to study its changes possibly linked with dynamical changes in the RTS characteristics of the investigated seismic area related with the loading regime of the dam.

As we mentioned earlier, though the number of events in the far zone can be spoiled by the EQs, not related to the reservoir-induced strain, the waiting times' (WT) distribution is less sensitive to (background) random events even relatively far from the dam, i.e. for R=100 km.

Results for the near zone R=50 km. In this case (for R=50 km) we included into complexity analysis, namely, RP and DFA methods, EQs below representative magnitude in order to fulfill the condition of used methods – to have at least 500 events.

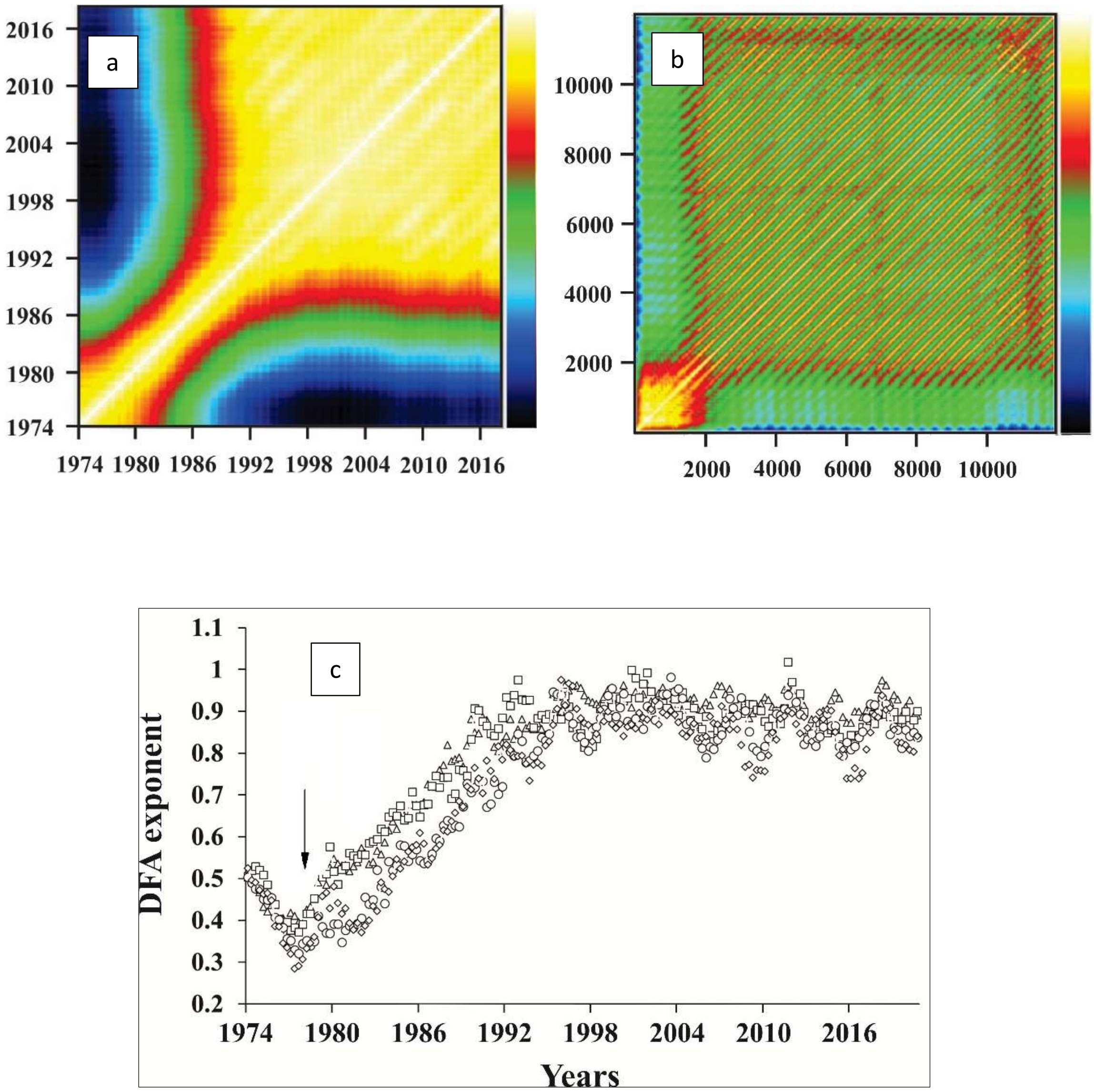


Fig 6 a, b, c. Recurrence plots of waiting times of EQs in local seismicity from the March 1974 to the March 2017 for R=50 km (a) and water level in the Enguri dam reservoir from the Apr 1978 to August 2017, where on the axes are day marks after the start of recharge. The blue cells correspond to a less recurrence and yellow ones – to better recurrence of events; (c) the DFA analysis reveals beginning of ordering in seismic events after 1980 and strong recurrence regime after 1986.

The distinct transitions from less regular to more regular pattern in seismic regime occur in 1985-1986 (a), when the WL change in reservoir became quasiperiodic, i.e. at the day mark 2000 in

Fig. 6b, which corresponds to the year 1985 (b); see also Fig. 3. Note light yellow diagonal lines in (a) after 1986, which is a mark of quasi-periodicity in RIS. Similarly, the DFA analysis (Fig. 6c) points to beginning of ordering in seismic events after 1980 and transition to strong recurrence regime after 1986.

Results for M2.2 *the far zone R=100 km*. We used DFA, RP, RQA and LZC methods for interevent and magnitude data sequences from Enguri seismic catalogue (1974-2017) involving 913 events above M2.2 occurred within 100 km distance from the dam.

In Fig. 7, we present results of DFA exponent α calculation of waiting time sequences. Calculation was done for 500 data length windows shifted by 1 data. DFA exponents for interevent times (Fig. 7) indicates gradual DFA exponent increase toward the period of reservoir water level periodic variation. Stronger increase took place in period starting from the 1984 and lasts till 2017. According to these results under influence of water level periodic variation in reservoir, long-range correlation clearly increased in earthquakes time distribution while earthquakes magnitude distribution is characterized by slight or negligible changes in a long-range features just at the beginning of observation period and after 200th window. The DFA for earthquakes magnitude distribution is characterized by slight or negligible changes in a long-range features.

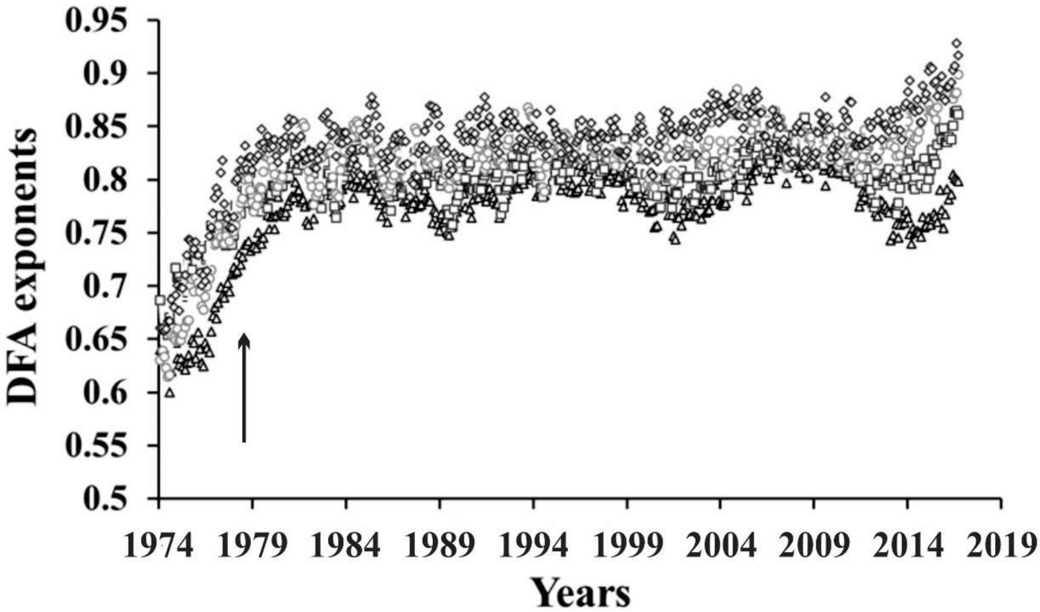


Fig. 7. DFA exponents of waiting times' sequences (M2.2 threshold) around Enguri reservoir (100km) 1974-2017. Polynomial fit from 2 to 5. (triangles P=2, squares p=3, circles p=4, diamonds p=5). Arrow marks the beginning of lake recharge; long-range correlation increases after 1984.

We applied also RQA and LZC methods to waiting times and magnitude data sequences from the Enguri seismic catalogue (1974-2017). Calculation was done for 500 data length windows shifted by 1 data.

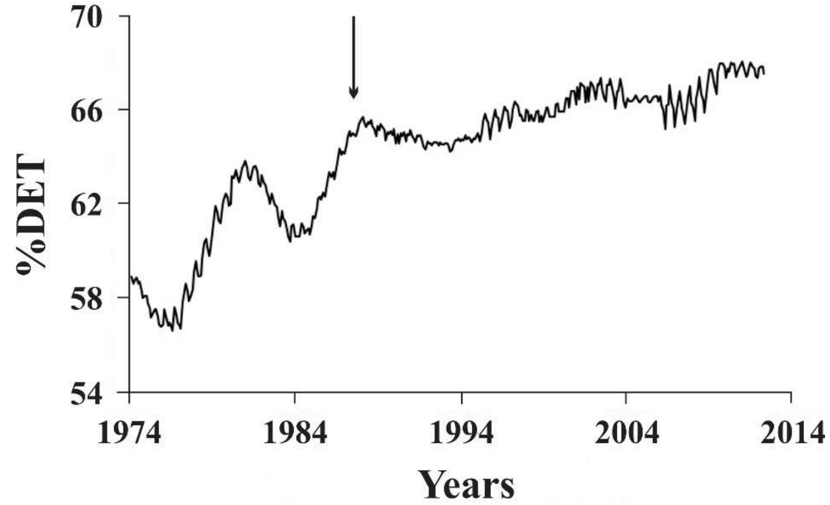


Fig 8. %DET of magnitude data sequences (M2.2 threshold) around Enguri reservoir (R=100km) 1974-2017. Note increased determinism in waiting times after 1986.

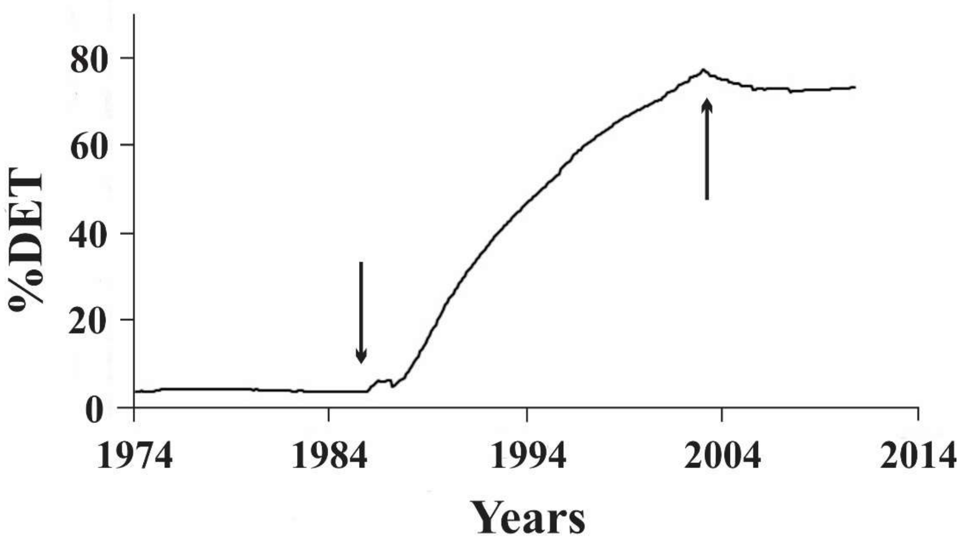


Fig. 9. %DET of interevent times sequences (M2.2 threshold) around Enguri reservoir (R=100km) 1974-2017. Note increased determinism in waiting times after 1986.

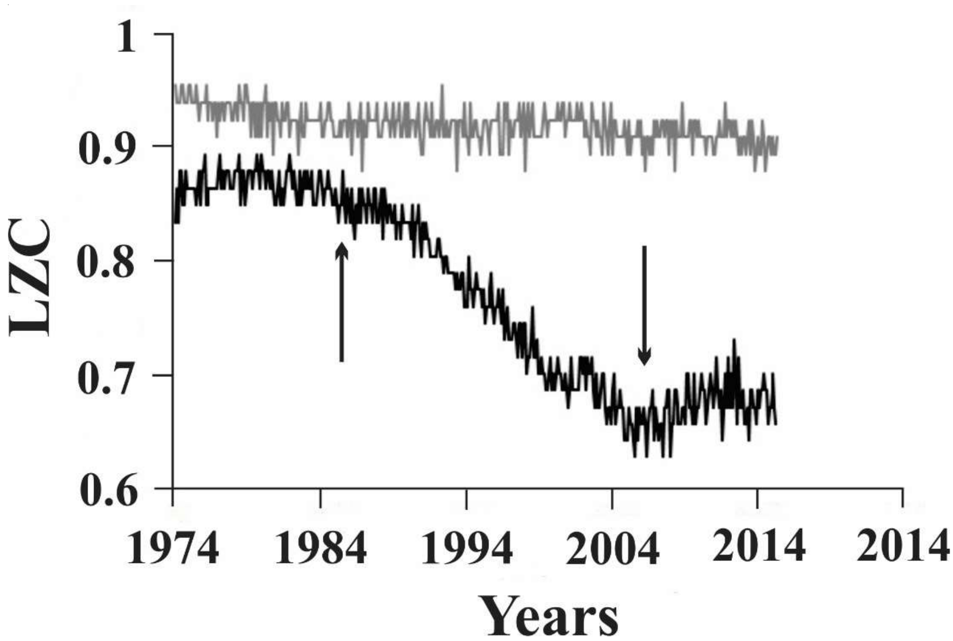


Fig. 10. Lempel and Ziv complexity measure calculated for (M2.2 threshold) around Enguri reservoir (R=100km) 1974-2017 using 500 data windows shifted by 1 data. Magnitudes sequence (grey) and interevent sequence (black).

5. Discussion: Nonlinear dynamics patterns in seismicity and water level variations in Enguri lake.

Let us consider results, obtained by different complexity analysis approaches: the methods abbreviation with a subscript *m* for magnitude time series and for the waiting times – by a subscript *wt*: for example, accordingly $(RQA)_m$ and $(RQA)_{wt}$.

i. We can elucidate the transition in seismic regime by $(DFA)_{wt}$ the intensive increase of the DFA exponent for the waiting times after 1984.

ii. Using RQA approach we reveal drastic changes in ETS dynamics for $(\%DET)_m$ after 1986 and for $(\%DET)_{wt}$ around 1986 and 2004, when the waiting times became maximal and stable.

iii. Using LZC we see that there are no changes in $(LZC)_m$, but $(LZC)_{wt}$ undergoes drastic changes in waiting times dynamics around 1986 and 2004.

Resuming, we can mark the dates of significant changes in the seismic time series dynamics around 1986 and in 2004 by both RQA and LZC methods.

Results of calculations presented in Fig. 6-10, convinces us that changes occurred in waiting times data sets are much stronger than in magnitude sequences. At the same time %DET of waiting times' sequence essentially increases and LZC noticeably decreases: both these effects point to the growth of order (recurrence) in ETS in the period 1985-1986. According to these results under influence of water level periodic variation in reservoir, long-range correlation clearly increased in earthquakes time distribution, while earthquakes magnitude distribution is characterized by slight or negligible change in long-range features.

Comparing dates of WL regime change and fault zone deformation patterns with transitions in the ETS dynamics, we can conclude, that the transition in RQA and LZC in 1984-1986 is connected with the beginning of the quasiperiodic load-unload process of the reservoir (see Fig. 3). Note, that from 1985-1986 the strain in the fault zone under Enguri Dam also reveals quasi-periodic decoration of the summary strain line (Fig. 3).

Thus, in the last period, beginning from the 1985-1986, the dynamics of local seismicity, especially, waiting times is much more ordered due probably to synchronization of seismic activity with WL variation regular pattern. This conclusion is confirmed by our earlier work where we carried out analysis of Enguri area seismic activity using the Singular Spectrum Analysis (SSA) technique in order to investigate the relationship of local seismicity with the reservoir water variations (Matcharashvili et al, 2008; Matcharashvili et al, 2010; Telesca et al; 2012; Telesca, Chelidze, 2018). We revealed the dominant one-year period in seismicity, which corresponds to seasonal load-unload of the Enguri dam lake: this period was absent in ETS of the area in the reference period before lake impoundment.

Conclusions

On the basis of the Recurrent Plots, Recurrent Quantification Analysis and Lempel-Ziv Complexity analysis carried out on interevent and magnitude sequences of Enguri area seismic catalogue, we conclude that influence of water level periodic variation makes time distribution of local earthquakes more regular (synchronized with water level variation) comparing to the period without such weak periodic influences. This means that nonlinear dynamics methods are effective in detection and quantitative analysis of Reservoir Induced Seismicity near large dams as they make possible to divide events, ordered by the impact of reservoir water regular strain from the background seismicity.

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