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Investigating the dynamical features of the time distribution of the reservoir-induced seismicity in Enguri area (Georgia)

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Abstract We analyzed the fractal and multifractal properties of the earthquake time series occurred around the Enguri dam in West Georgia by applying the methods of detrended fluctuation analysis and multifractal detrended fluctuation analysis. We examined the interevent time series in two periods: (1) 1960–1980, in which the investigated area was characterized by the natural seismicity; and (2) 1981–2012, in which the quasi-periodic change of the reservoir water level affected the earthquake generation. Our findings show that the water level variation may influence the fractal properties of earthquake temporal distribution in the local area around the Enguri dam. In particular, it is observed that the time distribution features of seismicity occurred in the second period are more persistent than the natural seismicity occurred in the first period. Furthermore, the seismic process of the second period shows a lower multifractal degree than that of the first period, indicating that the influence of quasi-periodic fluctuation of water level features the seismicity as more regular compared to the natural seismicity.

Keywords Reservoir-induced seismicity · Detrended fluctuation analysis · Multifractals

1 Introduction

It is known that large reservoirs may influence local seismic activity. Reservoir-induced seismicity has been reported in many cases worldwide in the last two decades

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(e.g., Simpson et al. 1988; Talwani 1997; Telesca 2010, 2011; Telesca et al. 2012a, 2012b, 2012c, 2012d, 2012e). Proposed mechanisms are change of strain in the earth's crust caused by the weight of water, or increased groundwater pore pressure that decreases the effective strength of the rocks around the reservoir (Simpson et al. 1988; Talwani 1997). This mechanism may work at the first stage of influence of large amount of water increasing to the maximal level. Later, for the period when the change becomes periodic, like for electric hydro-power stations, it was proposed as s mechanism of reservoir-induced synchronization of seismic process (Peinke et al. 2006; Matcharashvili et al. 2008).

Although several aspects related with reservoir-induced seismicity are well known, some other issues related with the changes of local seismic activity caused by water level still remain poorly investigated. One of these is related to the dynamical characterization of time distribution of seismicity in the area around large dams and water reservoirs.

Similarly to other seismic processes, also reservoir-induced seismicity is featured by a complex behavior that often is characterized by self-similarity, indicating that their dynamics can be interpreted as due to many components interacting over a wide range of time or space scales; such self-similarity is manifested by the existence of power-laws describing the main characteristics of the process (Turcotte 1997). Such power-law qualifies the process as fractal (Dimri 2000). (Telesca 2011) analyzed the time-clustering behavior of the 1996–2005 seismicity of Koyna–Warna region (India), which is a unique site where reservoir-triggered earthquakes have been continuously occurring over the last about 50 year. The scaling exponent α, estimated by using the Allan Factor method, a powerful tool to investigate clusterization in point processes, revealed co-seismic and pre-seismic enhancements associated with the occurrence of the major events. Telesca et al. (2012a) investigated the reservoir-induced seismicity observed in the Aswan area (Egypt) between 1986 and 2003 by using time-fractal methods. They found that the time dynamics of the aftershock-depleted seismicity, investigated by means of the Allan Factor, reveals that the time-clustering behavior for events occurred at shallow depths (down to 12.5 km from the ground) as well as for events occurred at larger depths (from 15 km down to 27.5 km) does not depend on the ordering of the interevent times, but mainly on the shape of the probability density functions of the interevent intervals. Moreover, the deep seismicity was more compatible with a Poissonian dynamics than shallow seismicity that was definitely more super-Poissonian. Additionally, the set of shallow events showed a periodicity at about 402 days, which could be consistent with the cyclic loading/unloading operations of the Lake Naser Dam.

In this paper, we investigate, in particular, the fractal properties of the time distribution of the earthquake series with and without the influence of reservoir water level variation in the Enguri area (West Georgia) that hosts the highest crest dam in Europe.

2 Methods

A seismic sequence can be represented by a temporal point process that describes events that occur at some random locations in time. This process can be described by the set of the interevent times, which is the series of the time intervals between two successive earthquakes.

The detrended fluctuation analysis (DFA) (Peng et al. 1993, 1995) was conceived as a method for detrending local variability in a time series, providing insight into its long-term variation features. This technique provides a quantitative parameter (DFA scaling exponent) that gives information about the correlation properties of the time series. The reason why the DFA is so useful is that it allows to detect scaling behavior in nonstationary time series, along with its really simple implementation; these characteristics feature the DFA as a very effective method in gaining information about an observational time series. Very often we do not know the reasons for underlying trends in collected data and we do not know the scales of underlying trends. DFA is a method for determining the scaling behavior of data in the presence of possible trends without knowing their origin and shape.

The DFA works as follows (Peng et al. 1993). The time series $x(k)$ (of length N) is firstly integrated and the so-called profile $Y(i)$ is determined. Then, $Y(i)$ is divided into boxes of size n, and in each box of length n, the polynomial local trend $Y_n(i)$ is calculated and removed from the profile. The root mean square fluctuation of the integrated and detrended series is, then, calculated:

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

This process is repeated for all the available scales (box sizes n). If the relationship between $F(n)$ and n is a power-law, the signal is fractal:

$$F(n) \sim n^{\alpha} \tag{2}$$

The scaling exponent α gives the information about the long-range power-law correlation properties of the signal. Scaling exponent $\alpha = 0.5$ corresponds to white noise (noncorrelated signal); when $\alpha < 0.5$, the correlation in the signal is anti-persistent; if $\alpha > 0.5$, the correlation in the signal is persistent. $\alpha = 1$ means uniform power-law behavior of $1/f$ noise, and $\alpha = 1.5$ represents a Brownian motion (Peng et al. 1993, 1995). The value $\alpha > 1.5$ corresponds to long-range correlations that may be related to both stochastic and deterministic correlations (Peng et al. 1995; Rodriguez et al. 2007).

One single scaling exponent is used to characterize the time dynamics of a monofractal process; but when only one scaling exponent is not sufficient, a multitude of scaling exponents is required and the process is multifractal. The multifractal detrended fluctuation analysis (MF-DFA) represents one of the most effective methods to evaluate the multifractal properties of a time series and is derived from the DFA (Kantelhardt et al. 2002).

The MF-DFA differs from the DFA in the calculation of the fluctuation function, which depends on the parameter q:

$$F_q(n) = \left[\frac{1}{N}\sum_{i=1}^{N}\left[Y(i) - Y_n(i)\right]^q\right]^{1/q} \tag{3}$$

Therefore, for negative q, the fluctuation function is more sensitive to the portions of the signal in which the fluctuation is small, and for positive q, it is more sensitive to those portions in which the fluctuation is large. For $q = 2$, the standard DFA procedure is retrieved. As similar to the DFA, the following function is obtained:

$$F_q(n) \sim n^{H(q)}, \tag{4}$$

where $H(q)$ is the generalized scaling exponent. For monofractal time series, $H(q)$ is independent of q, while when small and large fluctuations scale differently, then it depends on q, and in this case, the series is multifractal.

3 Results and discussion

We analyzed the earthquake catalogue of the Enguri area (West Georgia) within 90 km from the location of the dam. The construction of the dam started in 1970. The filling period ended in 1980, and after that, the water level variation became quasi-periodic. Therefore, we investigated the fractal properties of the interevent times (in min) in two time periods, 1960–1980 and 1981–2012 (Fig. 1). We considered both the whole and the declustered (Reasenberg 1985) catalogues for a threshold magnitude of 2.0.

Figure 2 shows the DFA fluctuation curves in the two investigation periods. We calculated the fluctuation curves for $p = 1, \ldots, 5$ where p indicates the degree of the fitting polynomial. Tab. 1 shows the scaling exponents with varying p.

It is striking that the scaling exponent is approximately unchanged with varying detrending polynomial degree. In particular, the period during the effect of the water level quasi-periodic variation is characterized by a more persistent interevent time series than the period before, with exponent around 0.7, significantly larger than 0.5, which characterizes the seismicity in the first period.

After declustering the catalogue by means of the Reasenberg's method (1985), the exponents are approximately unchanged; this indicates that the persistent properties of the series are robust with respect to the presence of possible aftershocks. However, also for the declustered catalogue, the persistence of the time distribution of seismicity during the quasi-periodic water level fluctuation is higher (Table 1).

A single scaling exponent is sufficient to describe the scaling behavior of a monofractal time series; however, for more complex and heterogeneous signals, a multitude of scaling exponents could be required. In this case, the signal is characterized by multifractal properties that could be well identified by means of the MF-DFA (Kantelhardt et al. 2002), which share with the DFA the robustness with respect to the presence of nonstationarities. The multifractality can arise from the different scaling behavior shown by small and large fluctuations in the signal. Therefore, an order parameter q is included in the algorithm of the MF-DFA to take into account the different behavior played by small and large fluctuations. In particular, negative q enhances the contribution of the small fluctuations, while positive q that of large fluctuations. The MF-DFA, whose implementation is described with

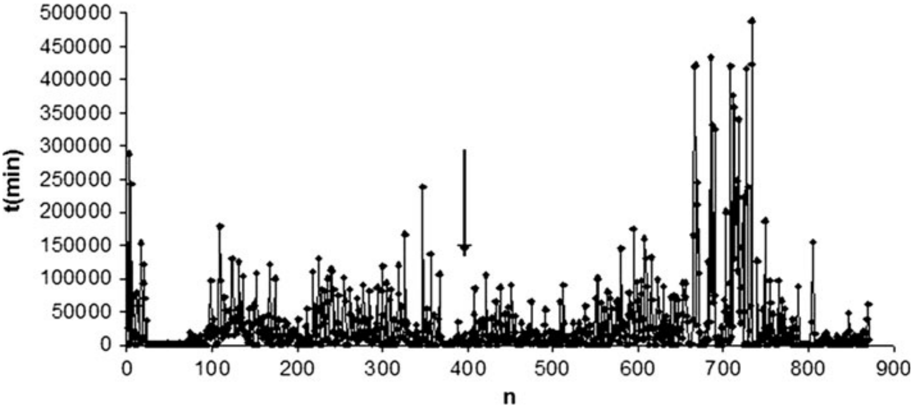

Fig. 1 Interevent time intervals from the whole catalogue of Enguri area in 1960–2012. The *arrow* indicates the separation in the two periods: *before the arrow* 1960–1980; *after the arrow* 1981–2012

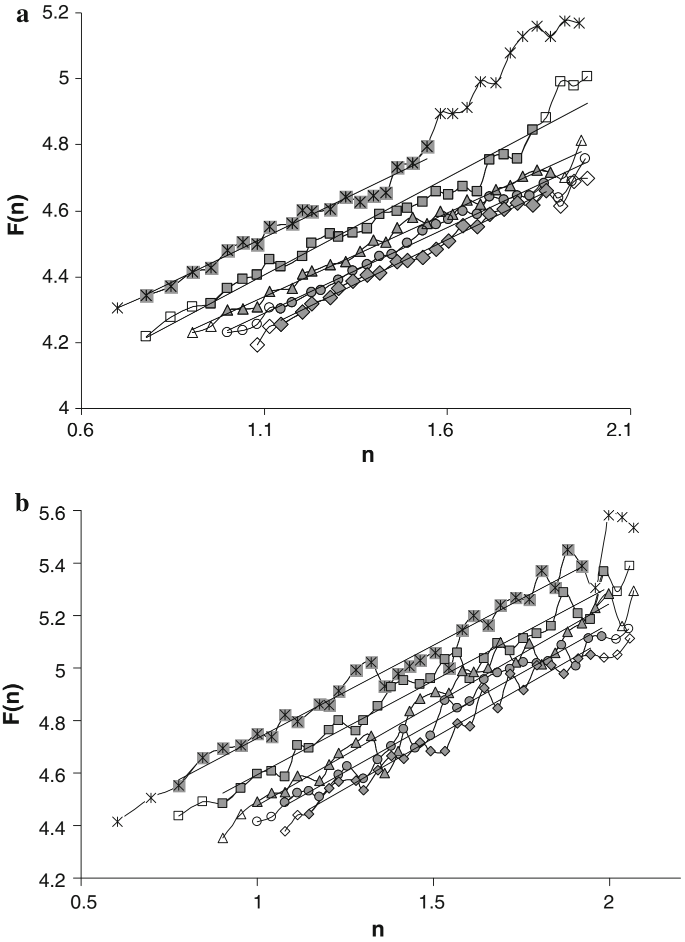

Fig. 2 DFA fluctuation curves for interevent time series from earthquake catalogue in 90 km area around Enguri dam in **a** 1960–1980 and **b** 1981–2012. Order of polynomial fitting $p = 1$ (*asterisks*), 2 (*squares*), 3 (*triangles*), 4 (*circles*), 5 (*diamonds*)

Table 1 DFA scaling exponent α of interevent time series

Order of fitting polynomial, p	Before influence of water level variation (1960–1980)	During influence of water level variation in reservoir (1981–2012)
1	0.53 ± 0.02	0.71 ± 0.03
2	0.54 ± 0.02	0.72 ± 0.03
3	0.50 ± 0.01	0.77 ± 0.03
4	0.51 ± 0.02	0.75 ± 0.03
5	0.54 ± 0.02	0.77 ± 0.04

detail in (Kantelhardt et al. 2002), leads to a power-law relationship $F_q(n) \sim n^{H(q)}$, where q is the magnitude-based weighting parameters, and $F_q(n)$ is the average q-th order fluctuation on time scale n (Fig. 3).

Figure 4 presents the results of MF-DFA for q ranging from -10 to 10 and $p = 4$ and 5, where p indicates the degree of the fitting polynomial (in order to not overburden picture, only results for $p = 4$ and $p = 5$ are shown). Figure 4a shows the variation of $H(q)$ with q for the period 1960–1980 and Fig. 4b for the period 1981–2012. Figure 4c shows the range of $H(q)$ $D(H(q))$ [the difference between the maximum and the minimum $H(q)$] with the degree p of the fitting polynomial; $D(H(q))$ can be considered as a quantitative measure of the multifractality (Koscielny-Bunde et al. 2006). We see that under the influence of water level periodic variation, $D(H(q))$ is smaller than the $D(H(q))$ of the natural seismicity occurring during the period 1960–1980 (Table 2).

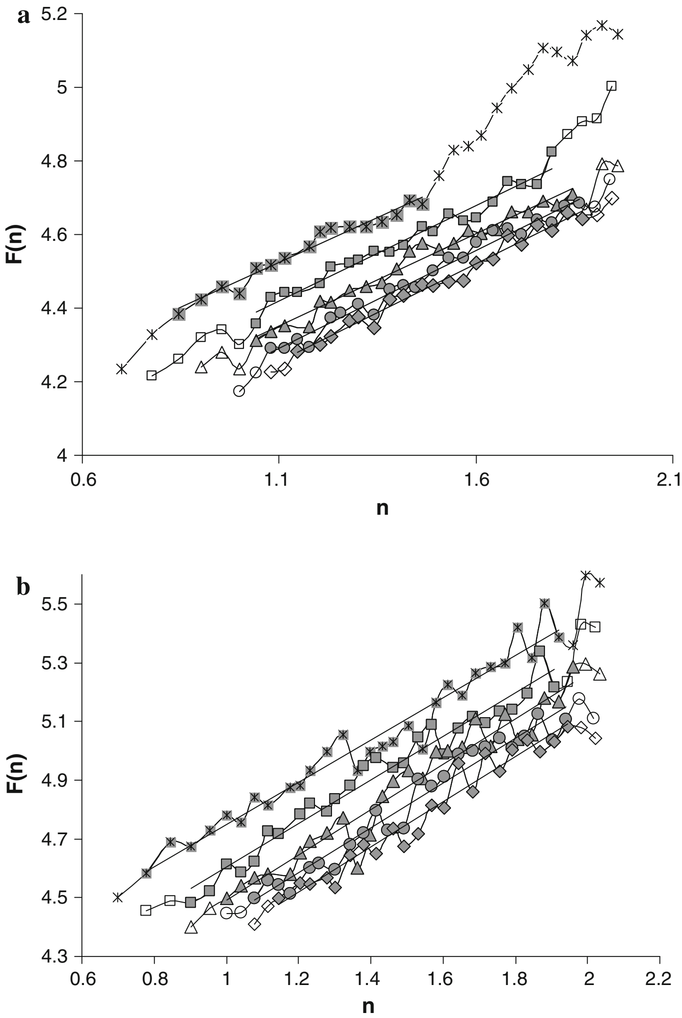

Fig. 3 DFA fluctuation curves for interevent time series from declustered earthquake catalogue in 90 km area around Enguri dam in **a** 1960–1980 and **b** 1981–2012. Order of polynomial fitting $p = 1$ (*asterisks*), 2 (*squares*), 3 (*triangles*), 4 (*circles*), 5 (*diamonds*)

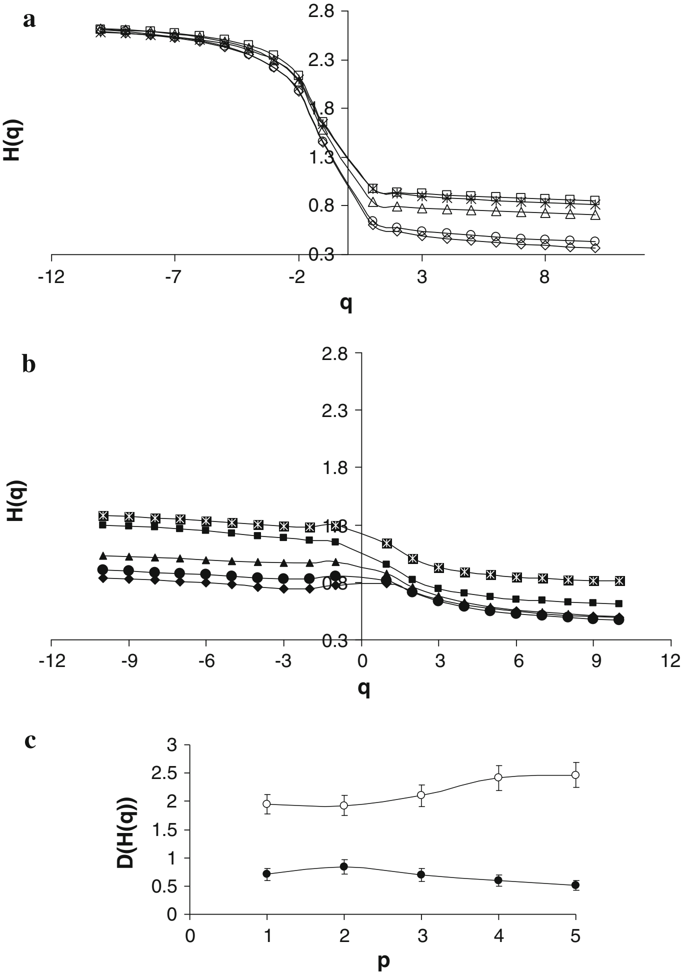

Fig. 4 *H*(*q*) of the interevent time series: **a** for the period 1960–1980 and **b** for the period 1981–2012. **c** Variation D(*H*(*q*)) with the degree of the fitting polynomial *p*; the period 1960–1980 is represented by *white circles*, while the period 1981–2012 by *black ones*

Table 2 DFA scaling exponent α of interevent time series from declustered catalogue

Order of fitting polynomial, *p*	Before influence of water level variation (1960–1980)	During influence of water level variation in reservoir (1981–2012)
1	0.49 ± 0.03	0.74 ± 0.04
2	0.52 ± 0.02	0.77 ± 0.03
3	0.50 ± 0.02	0.77 ± 0.04
4	0.53 ± 0.02	0.74 ± 0.03
5	0.53 ± 0.02	0.73 ± 0.03

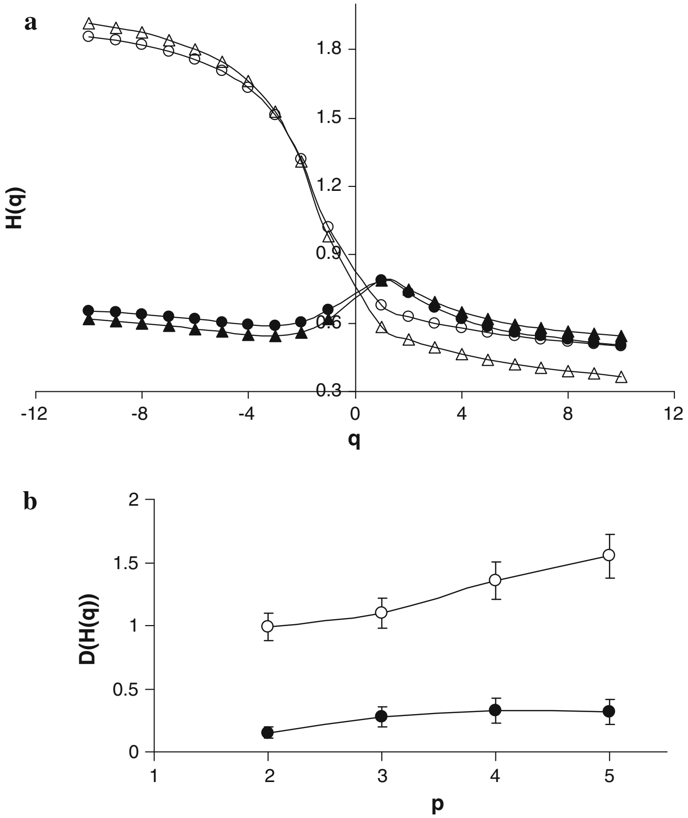

Fig. 5 **a** *H*(*q*) of the interevent time series of the declustered catalogue. The period 1960–1980 is represented by *white symbols* and the period 1981–2012 by *black symbols*. **b** Variation of the range of *H*(*q*) with the degree of the fitting polynomial *p*; the period 1960–1980 is represented by *white circles*, while the period 1981–2012 by *black ones*

Figure 5 shows the results for the declustered catalogue. These results are similar to those plotted in Fig. 4a, b. In Figure 5b, we see that similarly to the case of the whole catalogue, the range of *H*(*q*) decreases under water level periodic variation.

4 Conclusions

We investigated the fractal and multifractal properties of the earthquake temporal distribution around Enguri dam located in West Georgia during two periods: 1960–1980 and 1981–2012. The first period is characterized by natural seismicity, because it occurred before the construction and the filling of the dam; the second period is characterized by reservoir-induced seismicity affected by the quasi-periodic water level fluctuation.

It was found that water level variation may influence the fractal and multifractal properties of the temporal distribution of the seismicity of the Enguri area. In particular, the temporal dynamics of the seismic process under the effect of the quasi-periodic water level oscillation is more persistent and more homogenous (less multifractal) than that governing the natural seismicity typical of the area before the filling of the dam. These results point out that the dynamics of local seismicity around the Enguri dam became a more regular process modulated by the periodic oscillation of the water level.

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