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Relationship between seismicity and water level in the Enguri high dam area (Georgia) using the singular spectrum analysis

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Abstract. The declustered seismic catalog from 1965 to 2010 around the Enguri high dam reservoir in western Georgia was analyzed using the singular spectrum analysis (SSA) technique in order to investigate the relationship of local seismicity with the reservoir water variations. In particular, the seismic activity was analyzed in two periods: a "reference" period, from 1965 to 1970, before the start of dam building in 1971; and an "active" period, from 1978 to 2010, in which the influence of the reservoir was significantly effective on the seismic activity (since the first flooding of the dam occurred in 1978). The SSA was applied to both the monthly number of earthquakes and the time series of the monthly mean of the water level. The first four reconstructed components explained most of the total variance in both seismicity and water level. Clear signatures of the annual oscillation linked with the loading/unloading operations of the dam are present in the periodogram of the second and the third reconstructed components of the seismic activity during the "active" period. Such annual cycle is absent in the periodogram of the reconstructed components of the seismic activity during the "reference" period. This is a clear indication of the reservoir-induced character of the seismicity around the Enguri dam.

1 Introduction

The question of the relation between water level variation in deep reservoirs and seismic activity is a subject of intense interest from both the practical and scientific points of view. Field observations and scientific research from the two last decades provide arguments that are in favor of reservoir-induced seismicity (Talwani, 1997; Peinke et al., 2006; Telesca, 2010, 2011; Telesca et al., 2012a). The strength of such reservoir-triggered earthquakes was found to be in the range from damaging earthquakes (Talwani, 1997) to micro-seismic emissions (Chander and Sarkar, 1993). According to several authors (Talwani, 1997), the phenomenon of reservoir-induced seismicity may take place either due to the change in the state of the Earth's crust stress caused by the weight of water, or by increased groundwater pore pressure that decreases the effective strength of the rocks around the reservoir. These mechanisms for reservoir-induced seismicity presume that the area is already under considerable tectonic stress that can be released due to the stored water in the reservoir. Consequently, seismicity induced by reservoir water should be a transient phenomenon. It will occur either immediately after filling the reservoir, or after a delay of a few months or even years depending on the permeability of the rocks beneath the reservoir. Even for those reservoirs that show a correlation between earthquake activity and the level of water stored in the reservoir, induced seismicity does not continue indefinitely, as it is limited by the amount of already accumulated tectonic energy. Therefore, once the stress and pore pressure fields are stabilised at new values, the reservoir-induced seismicity decreases. It is assumed that the earthquake hazard will then revert to the level it was before reservoir building due to decreased amount of local tectonic stress.

In the present study, we investigate the change in local seismic activity around Enguri hydro power station reservoir. This reservoir, whose arch dam is the highest in Europe, is located in western Georgia. Based on general assumptions of reservoir-induced seismicity at the start of large reservoir functioning, we focused on the possible influence

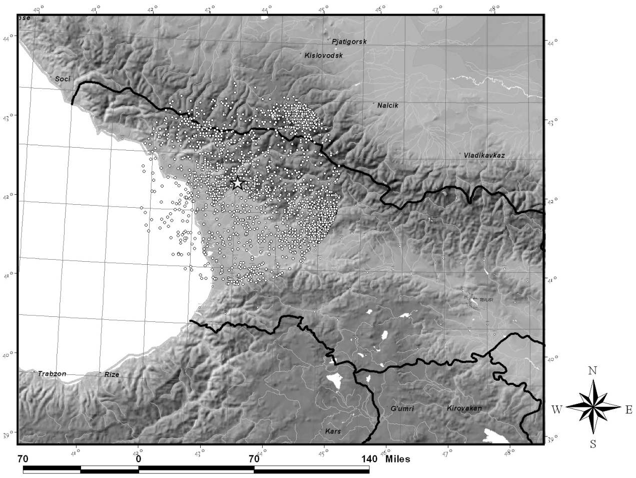

Fig. 1. Earthquake distribution in 100 km area around Enguri high arch dam.

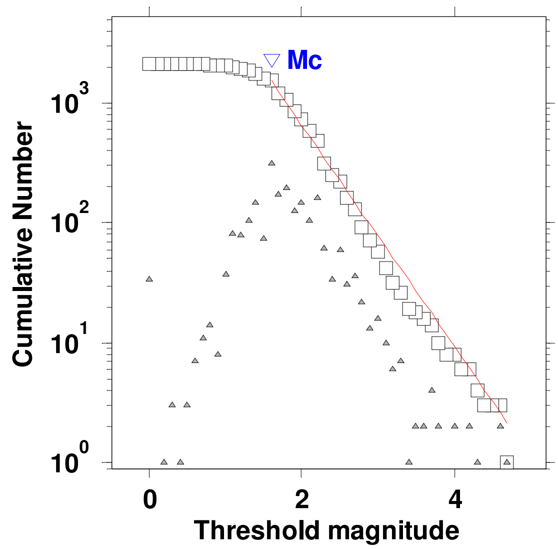

Fig. 2. Cumulative number of earthquakes vs. threshold magnitude during the period 1978-2010. The squares indicate the cumulative distribution, while the triangles indicate the binned frequency distribution.

of reservoir water level periodic variation on the changes in dynamical features of local seismic activity.

The structure of the paper is as follows. The seismicity and water level data are presented and preliminarily analyzed in Sect. 2. Section 3 describes the method of singular spectrum analysis (SSA), which will be used to investigate the temporal fluctuations of the monthly number of earthquakes and the monthly mean of water level. Section 4 shows the results, and the conclusions are depicted in Sect. 5.

2 Data

The seismicity of the area around the Enguri high dam from 1978 to 2010 was extracted from Caucasian Seismic Catalogue compiled by the Institute of Geophysics, Georgian Academy of Sciences. We selected the events whose epicentral distance from the location of the dam was less than 100 km (Peinke et al., 2006).

Before analyzing the relationship between the seismic activity and the water level, the catalog was declustered to avoid bias connected with the presence of aftershock clusters following the largest shocks. Applying the well-known Reasenberg (1985) method of declusterization, we obtained a declustered catalog of 2131 events with magnitudes $m \leq 4.7$ and with focal depths $h \leq 32$ km. The Gutenberg–Richter (1944) analysis was then performed to estimate the range of magnitudes within which the catalogue could be considered complete. Defining the completeness magnitude m_c as that at which a power law could model at least 90 % of the frequency–magnitude distribution (Wiemer and Wyss, 2000), we estimated $m_c = 1.6$ with $b = 0.92 \pm 0.02$ (Fig. 1). The b-value estimated for the Enguri high dam area is higher than that estimated for the entire Caucasus area, which is about 0.72 (Telesca et al., 2012b); this is one signature of the reservoir-induced nature of the Enguri seismicity.

Figure 3 shows the monthly mean of water level (red) and the number of events (blue) that occurred in the Enguri area with $m \geq 1.6$. Several patterns can be observed. (i) At the beginning, during the preliminary flooding of the territory and first stages of reservoir impoundment, the water level sharply increases during the first 8 months from the mean value of 335 m above sea level to about 410 m above sea level (indicated by box 1); about two years later the seismic activity reaches the highest value, 28 events with $m \geq 1.6$ (indicated by arrow a). (ii) From month 48 to month 128 (box 2), the water level increases from about 410 m to about 509 m, manifesting annual oscillatory behavior with maximal amplitude year by year; during this period of increased filling, the seismic activity does not show particularly high values. However, about two years after the maximal water level, reached in month 128, the seismic activity again shows a very high value, 22 events (indicated by arrow b). (iii) From the month 128 to the month 190, the seismic activity decreases, and later, until the end of 2010, it remains approximately constant; during this period the water level is characterized by an annual oscillatory behavior, with amplitude approximately constant. (iv) During the whole observation period, the seismic activity features approximately two different rates: from the beginning to month 165, the rate of about 8 events/month, and from month 186 to the end, the rate of about 0.8 events/month.

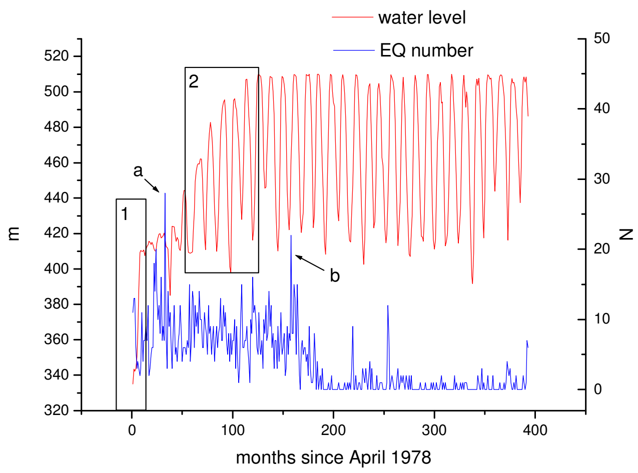

Fig. 3. Monthly number of earthquakes (blue) and monthly mean water level (red).

3 Methods

The aim of the analysis of geophysical time series is mainly the identification and possibly quantification of temporal structures, like cyclic behaviour, scaling, or anomalies with respect to some background behaviour. Such analysis is complicated by the stochastic nature of geophysical records and the range of natural influences these are susceptible to (Crockett et al., 2010).

The use of specific decompositional techniques in decomposing a non-stationary and aperiodic signal into several components on the basis of its frequency or correlation content effectively "de-noises" the series by allowing components of interest to be isolated from others that could weaken the information-containing components. Two decompositional methods are generally used, the Empirical Decomposition Method (EMD) (Huang et al., 1998) and the Singular Spectrum Analysis (SSA) (Vautard and Ghil, 1989). The EMD considers a signal to be given by a set of layers (Intrinsic Mode Functions, IMFs), each corresponding to a frequency content, built onto an aperiodic underlying state (the residual signal). The SSA, instead, is a Principal Components Analysis (PCA) technique in which the set of input vectors comprise a time-series and phase-lagged copies of itself, and is based substantially on a sort of autocorrelation.

The SSA provides a decomposition of relatively short and apparently noisy signals into a sum of a small number of independent and interpretable components, such as slowly varying trend, oscillatory components and structureless noise (Hassani, 2007). For a normalized signal (zero mean and unitary variance) y_i, with i varying from 1 to N (length of the signal), and a lag M, the eigenvalues λ_k and eigenvector E_{kj} of the Toeplitz lagged correlation matrix

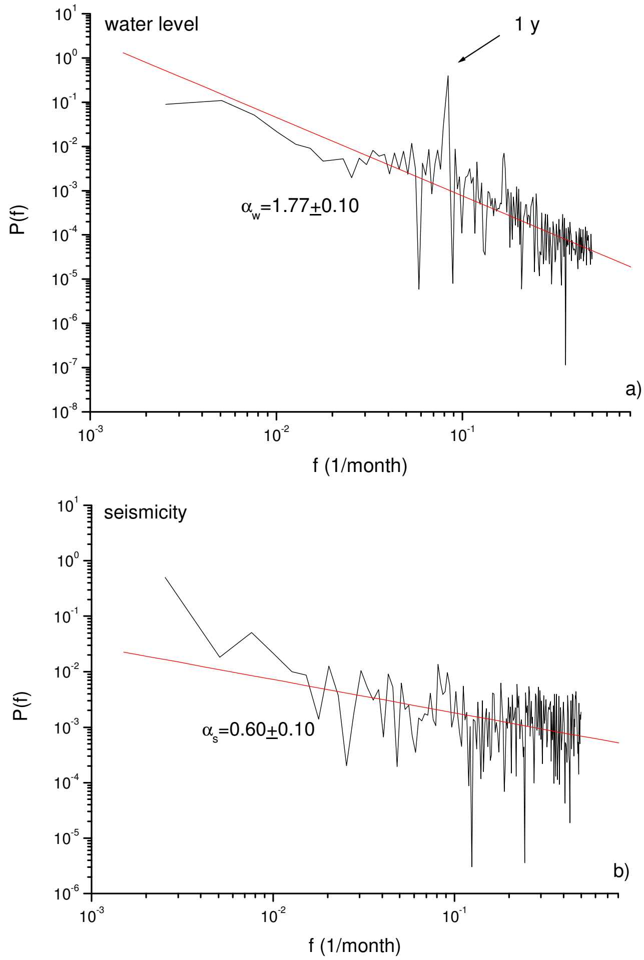

Fig. 4. Power spectrum of the monthly water level **(a)** and the monthly number of events **(b)**.

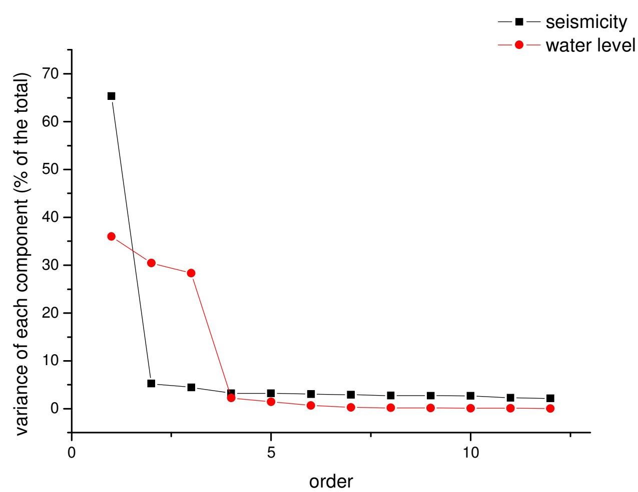

Fig. 5. Variance λ_k of each component of the investigated time series as percentage of the total variance.

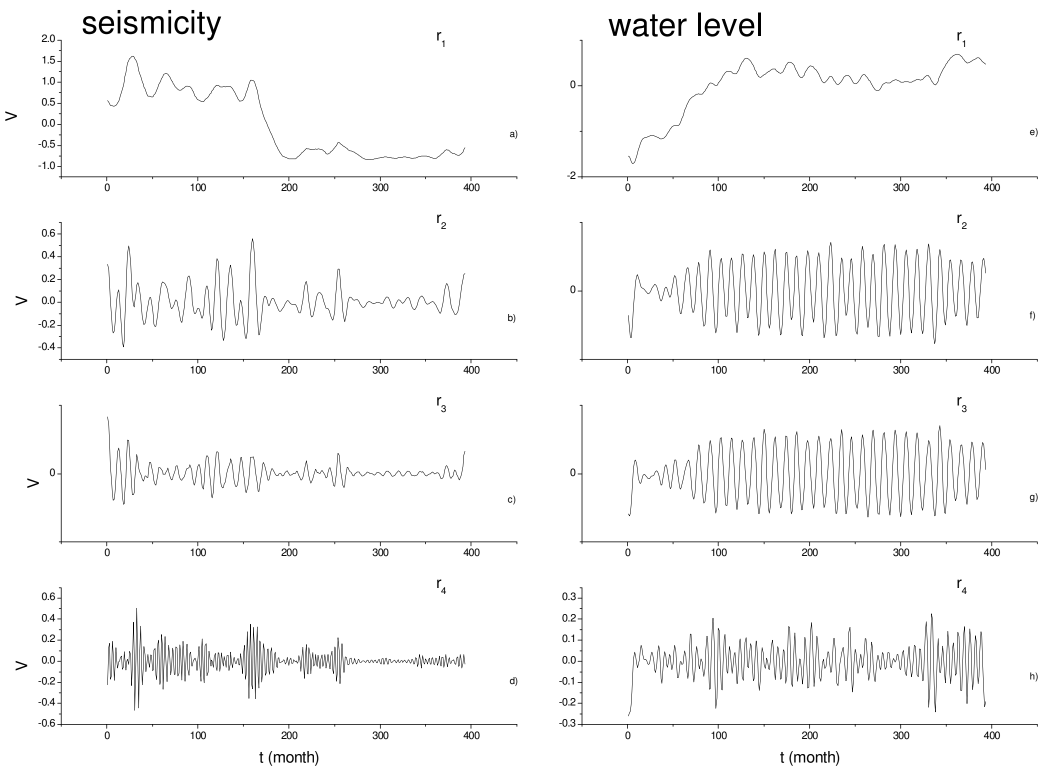

Fig. 6. The first four reconstructed components of both the monthly number of earthquakes **(a–d)** and the mean water level **(e–h)**.

$$c_j = \frac{1}{N-j}\sum_{i=1}^{N-j} y_i y_{i+j}, \quad 0 \le j \le M \tag{1}$$

are calculated and sorted in decreasing order of λ_k, with j and k varying from 1 to M. The k-th principal component is given by

$$a_{ik} = \sum_{j=1}^{M} y_{i+j} E_{jk}, \quad 0 \le i \le N-M. \tag{2}$$

The k-th reconstructed component of the signal is given by

$$r_{ik} = \frac{1}{M}\sum_{j=1}^{M} a_{i-j,k} E_{jk}, \quad M \le i \le N-M+1. \tag{3}$$

The fraction of the total variance of the original signal contained in the k-th r_{ik} is λ_k, so that, with the sorting used, the reconstructed components are ordered by decreasing information about the original time series (Schoellhamer, 2001). Generally, the first reconstructed components contain most of the variance, while the remaining ones contain merely noise. A pair of reconstructed components with similar λ_k typically represent each period less than M with significant energy in the original signal (Vautard and Ghil, 1989).

4 Results and discussion

As a preliminary analysis, we calculated the power spectrums of both the normalized monthly mean of water level (Fig. 4a) and monthly number of earthquakes (from 1978 to 2010) (Fig. 4b) by using the periodogram technique. Such an analysis allows getting information about the frequency content of a signal and identifying significantly powerful cycles. The water level shows an intense cycle at 1 yr superimposed on a power-law with spectral exponent $\alpha_W \sim 1.8$; the seismicity does not show any periodical feature, but only a power-law behavior with exponent $\alpha_S \sim 0.6$. In both cases, the power-law behavior suggests the presence of correlated structures in the time dynamics of the processes.

In order to unravel periodicities in the seismic activity, possibly synchronized (at same oscillation period) with the water level, we applied the SSA to both series and selected $M = 12$ to detect at least the annual cycle, which should be linked with the annual loading/unloading operations of the dam. Figure 5 shows the variance λ_k of each component as percentage of the total variance. We can see that the first 4 components, both in seismicity and water level, can explain the total variance; in particular for the seismicity the first 4 components explain almost 80 %, while for the water level they explain almost 97 % of the total variance. Therefore, we analyzed only the first 4 reconstructed components of both

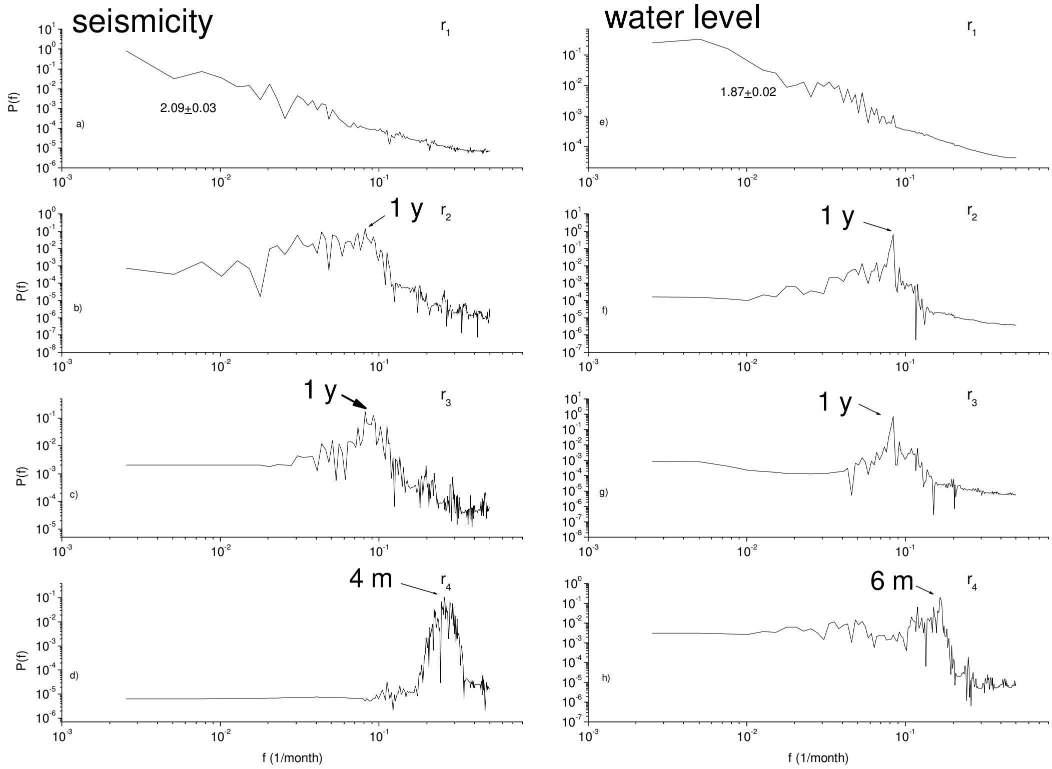

Fig. 7. Power spectrum of the first four reconstructed components shown in Fig. 6.

the monthly number of earthquakes r_{s} and mean water level r_{w} (Fig. 6). For each reconstructed component, we calculated the power spectrum, and the results are shown in Fig. 7. The first reconstructed components in seismicity ($r_{\mathrm{s},1}$) and water level ($r_{\mathrm{w},1}$) represent the long-term variation. During the dam filling (increase of the $r_{\mathrm{w},1}$ in Fig. 6e), $r_{\mathrm{s},1}$ is characterized by almost stationary high value (Fig. 6a), while during the periodically stationary phase of $r_{\mathrm{w},1}$ (Fig. 6e), the first reconstructed component of seismicity is characterized by almost stationary low value (Fig. 6a). The power spectra of both first components is very similar, displaying similar scaling behavior with very close values of the scaling exponents (~ 1.9 for water and ~ 2.1 for seismicity). The comparisons between the other reconstructed components also show interesting features: the second and the third components display the presence of the annual periodicity in both seismicity and water level (Fig. 6b, c, f and g); the fourth component in seismicity shows the presence of a 4-month cycle (Fig. 6d), while that in water level the presence of a 6-month cycle (Fig. 6h). Probably the 4-month and 6-month periodicities are just higher harmonics of the annual one, which represents the main cycle featuring both the water level and the seismic process in the Enguri high dam area, or appear due to high-order synchronization effects in seismic process caused by water level variation (Chelidze et al., 2010).

It is observed that the amplitudes of the annual cycle are approximately constant in the second and third reconstructed components of water, while the amplitudes of seismicity in those reconstructed components almost sharply decrease at the time in which the seismicity rate changes. The time of rate change defines two periods. In the first period, correspondent to territory flooding and reservoir preliminary filling, an increased amount of water volume obviously triggers release of seismic energy already accumulated in the area around the reservoir in the form of relatively strong earthquakes. In the second period, characterized by quasi-periodic change of water level, local seismic energy began to be released through series of small earthquakes according to slow quasi-periodic variability of reservoir water level. Possibly this mode of tectonic energy release prevents accumulation of large stress on the faults and, consequently, generation of large events. Similar regular behavior of stress release was observed in laboratory stick-slip experiments on the slider-spring model under application of the weak periodic mechanical or electromagnetic forcing (Peinke et al., 2006).

In order to check the robustness of the results, we applied the SSA to the time series of the monthly number of earthquakes from 1965 to 1970. This period can be considered as a “reference”, because the building of the dam started in 1971. We analyzed only the first 4 reconstructed components, whose sum explains almost the 84 % of the total variance.

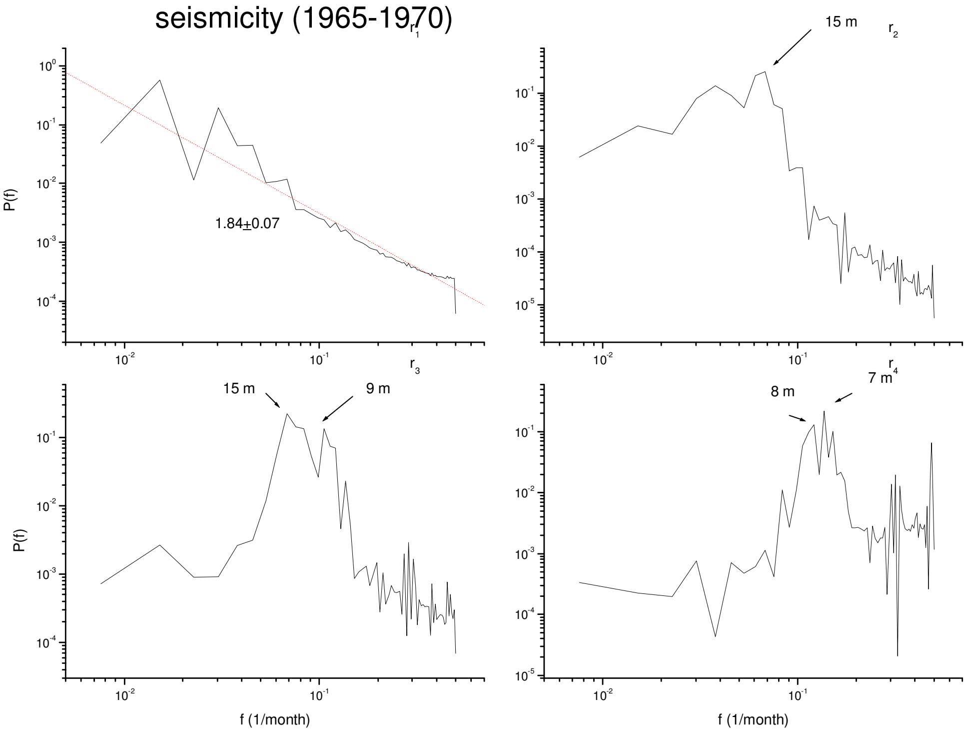

Fig. 8. Power spectrum of the first reconstructed components of the monthly number of earthquakes that occurred in the investigated area from 1965 to 1970.

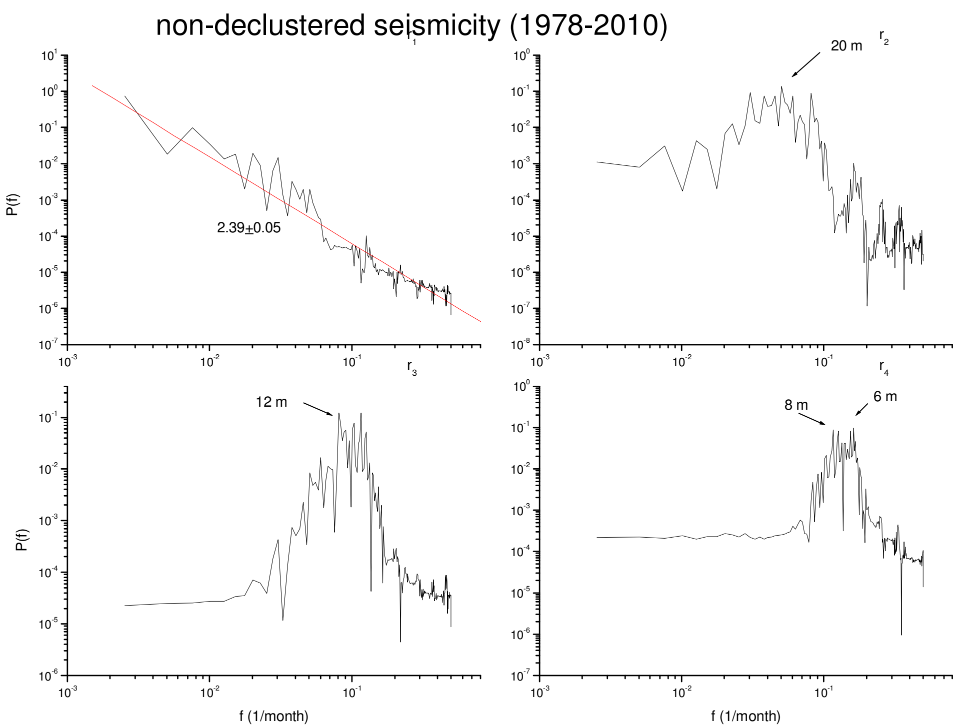

Fig. 9. Power spectrum of the first four reconstructed components of the non-declustered catalogue from 1978 to 2010.

Figure 8 shows the periodograms of the first 4 reconstructed components of the monthly number of events that occurred between 1965 and 1970. Besides the first reconstructed component, whose behavior indicates a long-term dynamic characterized by a persistence with exponent around 2, the other three reconstructed components show the main periodicities at about 15, 9, 8 and 7 months, but no evidence of the annual cycle is present. This confirms that a clear link between the reservoir water variations and the seismic changes really exists, and the annual synchronization between the water fluctuations and the seismicity around the Enguri dam is the main phenomenon of the reservoir-induced character of the earthquake activity of the area.

In order to see if the results can be influenced by the presence of the aftershocks, we applied the SSA on the non-declustered catalogue from 1978 to 2010. Figure 9 shows the periodograms of the first four reconstructed components of the monthly number of events. Only the third reconstructed component shows the cycle at about 12 months. Therefore, although the aftershock depletion has removed all those events not directly correlated with the reservoir dynamics (that could be interpreted as a kind of noise), the signature of the annual water cycle is still recognizable, even if only in the third reconstructed component. This indicates that the annual cycle is so strong as to be partially visible in the whole dataset.

5 Conclusions

In this work SSA method was used for the analysis of interrelation of water level and earthquakes around Enguri reservoir. A "reference" and an "active" time period were compared. Clear one-year periodicity in earthquake monthly counts was found during quasi-periodic change of water level, which is absent in the earlier time interval. It is concluded that seismic process around Enguri dam is linked with water level quasi-periodic variation, with the major one-year cycle and some higher harmonics.

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