Chapter 17

Earthquakes' Signatures in Dynamics of Water Level Variations in Boreholes

T. Chelidze, T. Matcharashvili, and G. Melikadze

Abstract It is known that variations of water level represent an integral response of aquifer to different periodic as well as non-periodic forcing, including earthquake-related strain generation in the earth crust. Quantitative analysis of impacts of separate components in the observed integral dynamics remains one of the main geophysical problems. It is especially important for non-periodic processes related to the earthquake generation, taking into account their possible prognostic value. We can formulate the problem as a nonlinear analysis of hydrological anomalies "triggered" by both the earthquake preparation and post-seismic processes.

In the present study, the dynamical complexity of water level variations has been analyzed. The dependence of dynamics on the presence of periodic components in the data records (time series) under study was investigated. Modern tools of time series analysis such as complexity measure and singular value decomposition technique have been used. Values of Lempel-Ziv complexity of water level records before and after the Spitak and Racha earthquakes, both original and reconstructed by singular value decomposition, were analyzed. The main purpose was to study dynamical response of water level variation to increased seismic activity around boreholes. Spectral characteristics, Shannon entropy and mutual information of water level variation time series were calculated. It is shown that most of boreholes are responding to changes caused by seismic activity, but some are not. This can be explained by the complexity of geological and stress field structures. Sensitive boreholes reveal some general features, such as an increase of the order in water level variability in separate boreholes and a decrease of functional relationship between water level variations in pairs of different boreholes before a strong earthquake.

T. Chelidze (✉), T. Matcharashvili, and G. Melikadze
M. Nodia Institute of Geophysics, 1 Alexidze str, 0171 Tbilisi, Georgia
e-mail: tamaz.chelidze@gmail.com; matcharashvili@gtu.ge

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17.1 Introduction

Generally speaking, the water level (WL) variation in deep boreholes is caused by a number of different factors. One of the most important factors is a strain change in the upper Earth crust. In fact, deep boreholes represent some kind of sensitive volumetric strainmeters, where water level responds to the deformations of about 10^{-7} –10^{-8}. Hence, it is obvious that the process of water level variations will reflect also the integral response of aquifer to the earthquake-related strain redistribution in the Earth crust (Kumpel, 1992; Gavrilenko et al., 2000). The network of water regime boreholes existing in Georgia allows to create a spatial picture of the strain field and observe its evolution in the time domain. The retrospective analysis of materials shows that a characteristic annual course of levels of underground waters is disrupted in the period of strong earthquakes (Spitak, 1988; Racha, 1991; Java, 1991; and Barisakho, 1992). The area of compression is characterized by underground waters level increasing in comparison to the normal trend, and the area of dilatation – by its decrease (Melikadze and Ghlonti, 2000). Therefore, investigation of water level variations may provide additional understanding of the dynamics of processes related to earthquake preparation in the earth crust (Manga and Wang, 2009). Nevertheless, the problem of relationship between changes in dynamics of water level variation and strong earthquake preparation still remains practically unsolved (King et al., 1999).

In the present study we have investigated the dynamics of WL variation in the network of deep boreholes on the territory of Georgia. The aim of research was to clarify the character of influence of seismic processes on dynamics of water level variation. Taking into account practical problems and scientific discussions related to understanding of seismic processes, investigation of influence of seismic activity on the dynamics of water level variation is important both from scientific and practical points of view.

17.2 Methods of analysis

As the water level variation in deep boreholes is caused by a number of endogenous and exogenous factors, we prepared a special programme for defining the tectonic component; it calculates the theoretical signal composed of a sum of reduced values of atmospheric pressure, tidal variations and precipitation. In order to extract the geodynamical signal, correlation analysis between the real values of WL and the theoretical signal has been made (Gavrilenko et al., 2000; Melikadze and Ghlonti, 2000). The program gives a possibility to calibrate values of deformation in 10^{-8} range by comparison of geodynamic signals with tidal variations.

The WL variation data sets of deep boreholes in Georgia have been analyzed by modern methods of nonlinear dynamics. The network of underground water regime observations was set up in the Caucasus in 1985. Since that time, a network comprising

50 sub-artesian boreholes of different depths (ranging from 250 m down to 3500 m) has been functioning in the Caucasus. The Georgian network consists of 10 boreholes and covers the entire territory of Georgia. The present study is based on analysis of hourly water level variations time series of 6 boreholes, namely: Lisi (44.45 N, 21.45 E), Borjomi (43.27 N, 41.52 E), Akhalkalaqi (43.34 N, 41.22 E), Ajameti (42.49 N, 42.10 E), Marneuli (44.52 N, 41.26 E), and Kobuleti (41.48 N, 41.47 E) boreholes. Typical records of hourly water level variations are presented in Fig. 17.1. Depending on the availability and quality of data, time series of different length were analyzed. The longest one covers approximately two years (01.03.1990 through 29.02.1992) and the shortest one covers one month (11.10.1988 through 12.12.1988).

At first we calculated power spectrum as well as the power spectrum regression exponent (Allegrini et al., 1995; Feder, 1988) of water level time series. In order to evaluate the character of probability distribution, the Shannon entropy S:

$$S = -\sum_{i=1}^{N} P_i \log(P_i),$$

where P_i is the probability of an event to occur within box i, was calculated using different time-span sliding windows (Kantz and Schreiber, 1997; Schreiber, 2000). Then, in order to evaluate the strength of functional dependence between water level variations in different boreholes we used a measure of statistical independence between two variables, the averaged mutual information (Cover and Thomas, 1991; Kantz and Schreiber, 1997):

$$I(T) = \sum_{i=1}^{N} P(x(i), x(i+T)) \log_2 \left[\frac{P(x(i), x(i+T))}{P(x(i))P(x(i+T))}\right],$$

where $P(x(i))$ and $P(x(i+T))$ are, respectively, the probabilities of finding $x(i)$ and $x(i+T)$ measurements in time series, $P(x(i), x(i+T))$ is the joint probability of finding measurements $x(i)$ and $x(i+T)$ in time series, and T is the time lag.

In the present study we analyzed the integral dynamics of water level variability. Therefore we avoid any linear filtration or signal separation, only nonlinear noise reduction procedure (Kantz and Schreiber, 1997; Hegger et al., 1999) after zero mean and unite variance normalization have been carried out.

17.3 Results and discussion

As follows from our analysis, the response of WL variation of analyzed boreholes to the increased regional seismic activity varies from case to case. Indeed, it is shown in Fig. 17.1 that the water level change coinciding in time with strong Racha earthquake is essential for Lisi borehole. At the same time, during the same period, amplitudes of variation of water level in Akhalkalaki and Kobuleti boreholes are

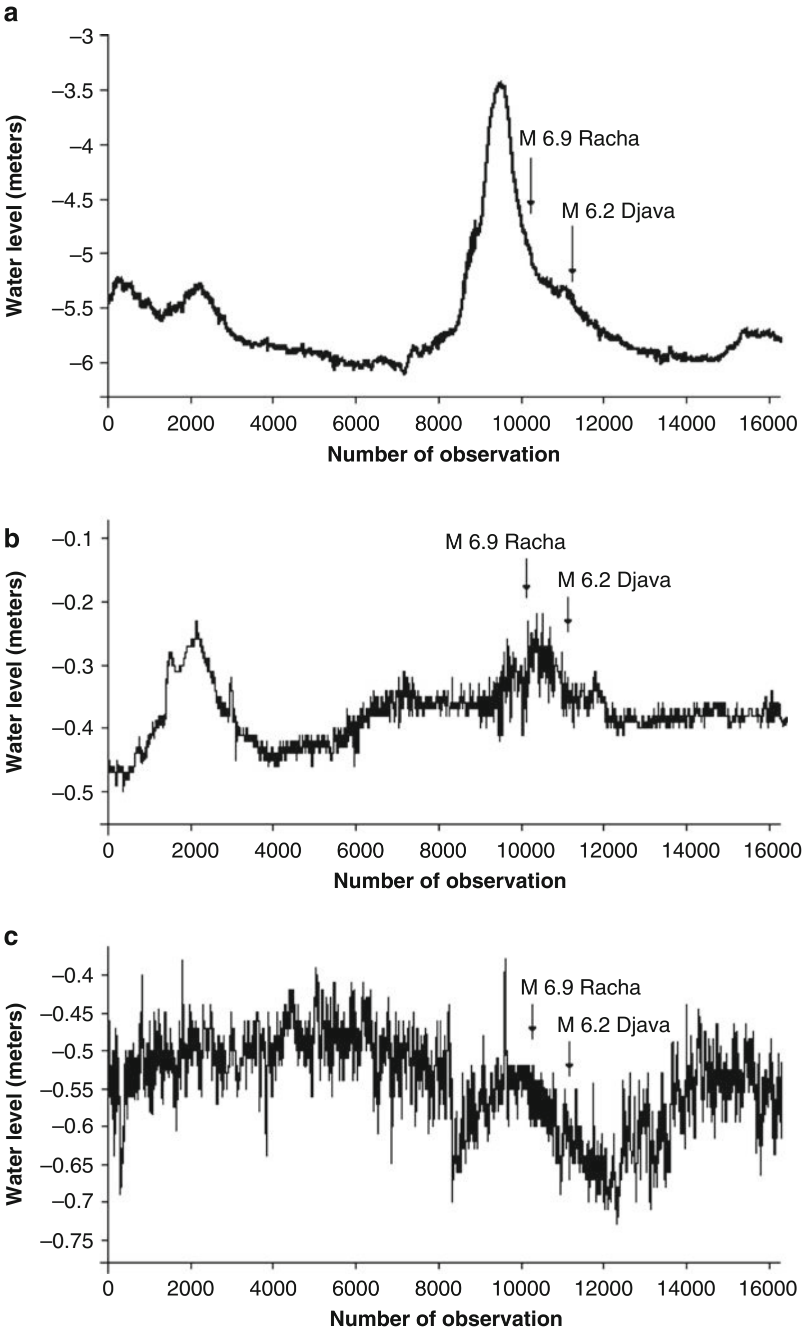


Fig. 17.1 Water level variation at (**a**) Lisi, (**b**) Akhalkalaki and (**c**) Kobuleti boreholes for the time period 01.03.1990−29.02.1992

rather small or even practically unchanged comparing to the Lisi borehole. This can be explained by the complex character of stress field in the region (Melikadze and Ghlonti, 2000).

Before the Spitak event, the infringement period of the background regime appeared in separate wells at different times and with different intensities: in Lisi from 25.11.88; in Borjomi from 28.11.88; in Lagodekhi from 28.11.88. First of all, the infringements are seen on boreholes located in northern part of the structure, in the zone of strongest compression, and later in the south. As a rule, the character of anomaly in the compression zone has a positive bay shape (Lisi, Borjomi, Lagodekhi, etc.), and in the stretching zone — the sawtooth or negative bay (Marneuli, etc.). The above-mentioned sequence of infringement occurrence can be caused by directional development of deformation processes.

The same is proved also by the materials of Racha earthquake (29.04.91) obtained from the boreholes network. The anomalies in hydro-geo-deformation field divide the Caucasus in two parts and have been precisely fixed before the event. The division between the zones passed along a deep tectonic fault of sub-meridian orientation. The zone of largest gradient specified the place of future disaster, coinciding with the point of junction of the fault.

Deformation processes covered the whole observed territory of the Caucasus. Despite the complicated geological structure of the territory and different strain-sensitivity of boreholes, the general tendency of changes is noticed in the underground waters regime. In boreholes located in the compression field, an abnormal rise of water level is observed (in Akalkalaki from 01.02 by +10 cm; in Marneuli from 15.04 by +25 cm; in Lisi from 02.04 by +2 m; in Borjomi from 02.04 by +1 m; in Lagodekhi from 03.04 by +50 cm; in Chargali from 10.04 by +30 cm). The greatest deformations are in the Lisi borehole. In boreholes located in the stretching area, the water level decreases: Kobuleti from 20.04 by −10 cm; Gali from 10.04 by −0,5 meters; and Adjameti from 10.04 by −30 cm.

In the stress field, the transitive zone between deformations of different signs extends along the above-marked deep fault and crosses the epicentral zone, where the dipole deformation structure is created. Its presence confirms the existing ideas about the strain distribution in the source area of earthquakes (Fig. 17.10).

In general, the water level variation dynamics before the Spitak earthquake is also characterized by increased extent of regularity expressed by decreased Shannon entropy value, though it is not so evident as for the Racha event; there are still local minima (Fig. 17.3). At the same time, contrary to the Racha earthquake, here, after the strong event, the dynamics of water level variability in most cases becomes much more disordered than before: the Shannon entropy increases.

During the Spitak earthquake preparation period, within several months, a strong stretching sub-latitude deformation was formed in the future epicenter area, and a compression area appeared to the north of it. The expanding zone of stretching, besides the territory of Armenia, covers a part of southern Georgia (boreholes Marneuli and Akhalkalaki) and western Azerbaijan (borehole Sheki).

Within three months, the decrease of water level on the borehole Akhalkalaki against the annual “background” reached 20 cm, that makes a half of the maximal amplitude of seasonal fluctuations. On the Marneuli borehole, the decrease was much larger (up to 50 cm), and almost the whole amplitude of seasonal fluctuation was leveled by tensile deformation. On the Sheki borehole, the difference was up to 30 cm. In the compression zone, there is located the Borjomi borehole, where during six months the difference of the level, in comparison to the average, makes +1.5 meters, and Lisi, where it is up to +1 meter. The Lagodechi borehole changes are of the same order. During some period of time, the intensity increases; at the critical point of deformation, the lunar-solar tidal variations disappear in the underground waters, and the impact of barometric pressure disappears too. At this time, the strong endogenous factors which influence the water bearing horizon muffle the exogenous ones.

The appearance of anomalies before the Spitak event was distributed in time: Lisi - from 25.11.88; Borjomi - from 28.11.88; Lagodechi - from 28.11.88; Sheki - from 4.12.88; Novkhvani - from 4.12.88; Shemakha - from 6.12.88. It is evident that the anomaly first of all manifests itself in the boreholes located in the northern part of the structure, in the strongest compression zone, and later on in the south. As a rule, the anomaly in the compression zone has a positive bay shape (Lisi, Borjomi, Lagodekhi, Novkhvani, Shemakha etc.) and in the stretching zone it looks like the sawtooth or negative deviation (Marneuli, Sheki etc.). Thus, there is some regular pattern of the anomalous field evolution (Fig. 17.11).

All the changes described above are obviously related to the seismic activity, because in most cases they concur with strong earthquakes. Such a relation is evident from an analysis of the longest water level variability time series available for us. In Fig. 17.4, Shannon entropy for time series containing 16300 readings (01.03.1990 through 29.02.1992) analyzed by two-week span sliding windows are presented. It is shown that the dynamics of water level variation undergoes clear changes both before and after strong earthquakes. As it is presented in Fig. 17.4 a, over about 9-5 month period of time before the strong Racha earthquake, water level variation in Lisi borehole becomes strongly ordered. The Shannon entropy value of water level variation noticeably decreases for this period clearly preceding the strong earthquake. At the same time, immediately before the earthquake (over 30-15 days period) the water level variation became maximally disordered; the entropy value has substantially increased.

Generally similar is the situation for the long time series of Akhalkalaki borehole (Fig. 17.4 b), where about 8 months before the Racha earthquake the water level variation for short time period has minimal (but higher than for the Lisi borehole and for a much shorter time period) value of Shannon entropy.

Immediately before the strong earthquake, the water level variation in Akhalkalaki borehole also became maximally disordered and is characterized by practically the same extent of Shannon entropy as for the Lisi borehole. At the same time, the water level variation in Kobuleti borehole does not show the features observed for the other two boreholes (Fig. 17.4 c), which can be explained by a relatively large epicentral distance (King et al., 1999).

Thus, in two out of the three long time series analyzed, the dynamics of water level variation becomes more irregular two-three weeks before a strong earthquake. At the same time, it is important to mention that some boreholes may by insensitive (King et al., 1999) to changes caused by regional seismic activity (see, e.g., the results for Kobuleti borehole in Fig. 17.4 c).

In spite of the observed differences in absolute values of amplitudes of water level in different boreholes, the dynamics of variation still reveals some interesting features which may be related to regional seismic activity. All the water level variation time series analyzed are characterized by a broadband power spectrum. By their exponents of power spectrum regression, the process of water level variation in 20.5-day duration time series (600 data), generally can be attributed to the coloured type of noise, both before and after strong earthquakes (see, e.g., Tables 17.1 and 17.2). The obtained values of power spectrum exponents are typical for processes where the low frequency events (taking place on long time-scales) dominate in the total variability compared to the high frequency component (Pimm and Redfearn, 1988). In this respect, as it follows from Tables 17.1 and 17.2, there are no significant differences in spectral characteristics of water level variations during or after strong earthquakes (excluding water level variation in Ajameti borehole for rhe Spitak and Borjomi borehole for the Racha earthquakes).

Thus, spectral characteristics of water level variability do not react on the level of regional seismic activity which significantly increased for the analyzed time period.

In spite of this integral insensitivity, we tried to clarify some details of the fine dynamical structure of process of interest on the shorter time scales. For this purpose, the Shannon entropy values of 10-day-span sliding windows of longer water level variation data sets (including time periods both before and after large earthquakes) have been calculated. In Fig. 17.2, it is shown that the dynamics of water level variability on 10-day time scale undergoes noticeable changes both before and after the Racha earthquake. The same is true for the aftershock of the

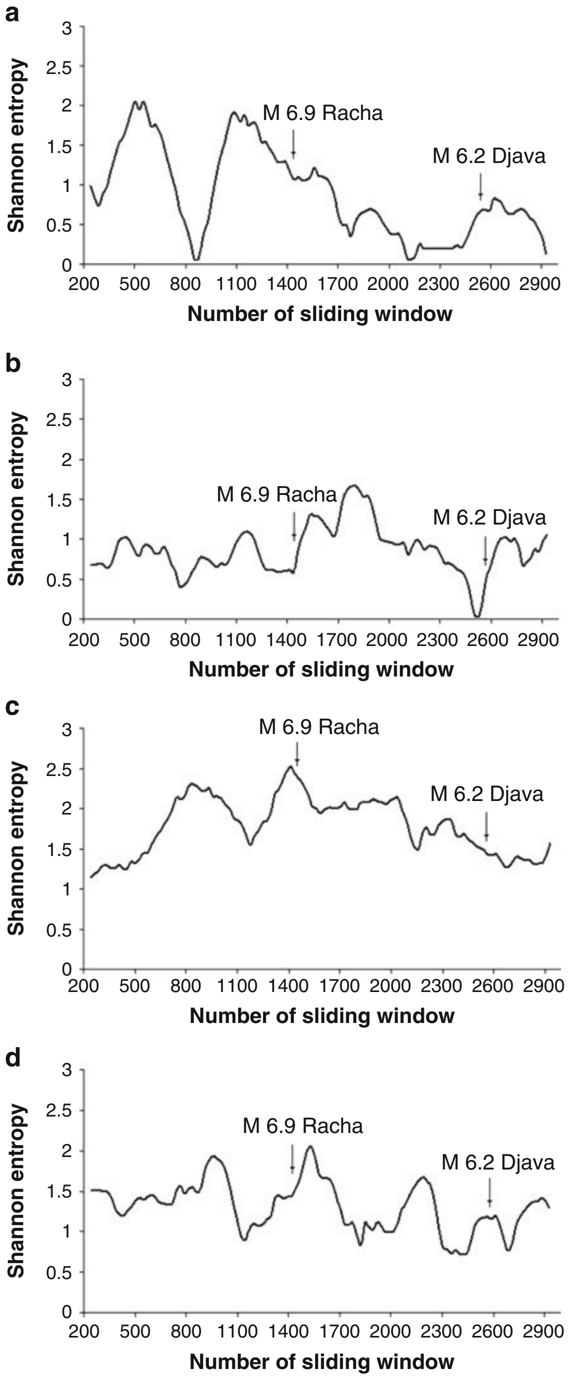
Table 17.1 Power spectrum regression exponents of water level variation before and after the Spitak earthquake

	Axalkalaki	Borjomi	Ajameti	Lisi
Before	−1.59 ± 0.08	−1.69 ± 0.09	−2.13±0.02	−1.74 ± 0.08
After	−1.66 ± 0.08	−1.83 ± 0.03	−1.87 ± 0.07	−1.82 ± 0.03

Table 17.2 Power spectrum regression exponents of water level variation before and after the Racha earthquake

	Axalkalaki	Borjomi	Ajameti	Lisi
Before	−1.81± 0.09	−1.57± 0.08	−1.84 ± 0.05	−1.80 ± 0.01
After	−1.86 ± 0.07	−1.79 ± 0.05	−1.93± 0.08	−1.82 ± 0.03

Fig. 17.2 Shannon entropy values of (**a**) Lisi, (**b**) Lagodekhi, (**c**) Akhalkalaki, and (**d**) Ajameti boreholes water level hourly records calculated for 240 data (10 day time span) sliding window at 24 hour step. Time of observation: 01.03.1991–30.06.1991



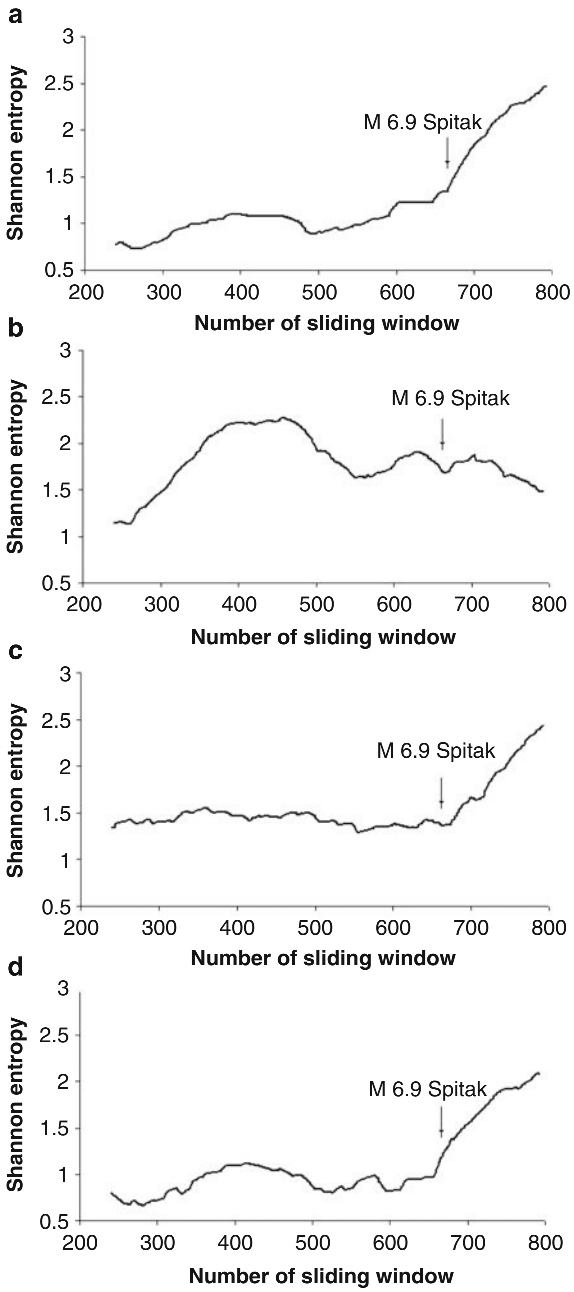


Fig. 17.3 Shannon entropy values of (**a**) Lisi, (**b**) Lagodekhi, (**c**) Borjomi, and (**d**) Marneuli boreholes water level hourly records calculated for 240 data (10 day time span) sliding window at 1 hour step. Time of observation: 11.10.1988–12.12.1988

Racha earthquake, M.6.2 Djava (15.06.1991) event. As shown in Fig. 17.2, in almost all the cases, the Shannon entropy of water level variability approaches their local extremes before the strong earthquake.

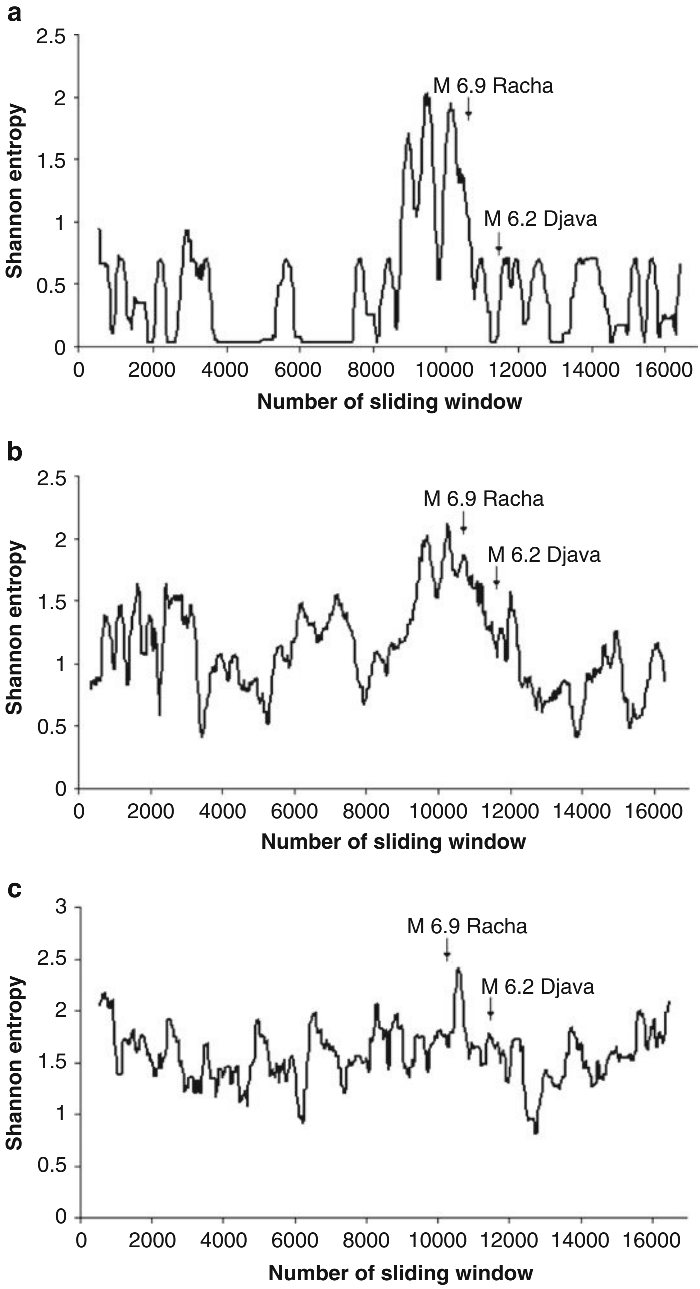


Fig. 17.4 Shannon entropy values of (**a**) Lisi, (**b**) Akhalkalaki and (**c**) Kobuleti boreholes water level hourly records calculated for 360 data (two-week time span) sliding window at 24 hour step. Time of observation: 01.03.1990–29.02.1992

It is also important to say that on the analyzed time scale and for the tested period of observation, the WL variation after the strong earthquake comes back to the background level.

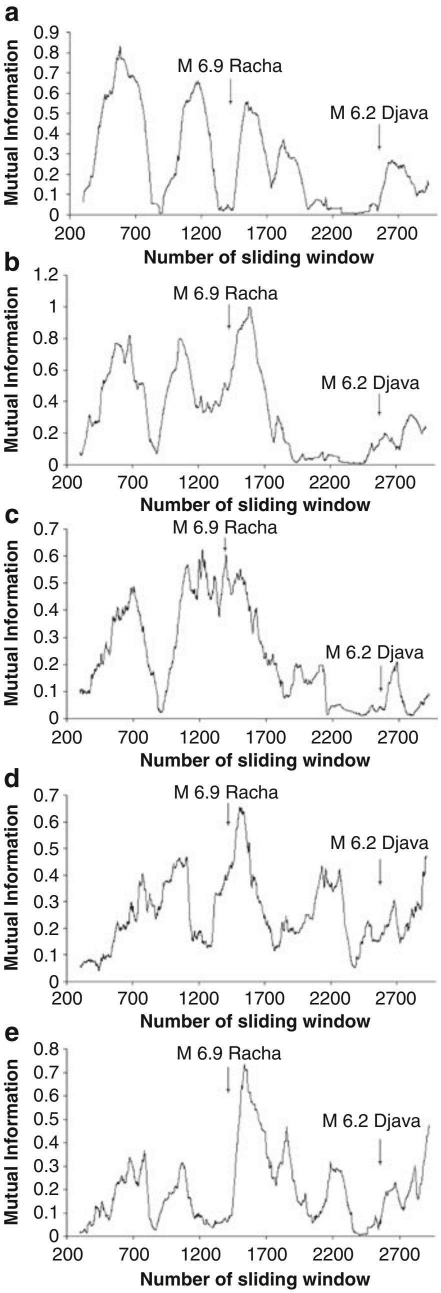
As there are important similarities in dynamical responses of water level variations for different boreholes to regional seismic activity, we have investigated the strength of functional dependence between them. For this purpose, we calculated averaged mutual information, the well known measure of statistical independence between two variables (Cover and Thomas, 1991; Kantz and Schreiber, 1997). The mutual information value is the most suitable parameter for these purposes, because unlike the linear correlation function, it takes into account nonlinear correlations too (Hegger et al., 1999). It is shown in Fig. 17.5 that the strength of functional relationship between water level variability in pairs of boreholes before, during, as well as after strong earthquake undergoes noticeable changes. The water level variability in different boreholes is maximally de-correlated over about two-to-three weeks period before the Racha event (mutual information values have their minima). It is important that this strong earthquake as well as its aftershock is preceded by brief sharp changes in extent of interdependence of variability in boreholes.

In most cases, the above-mentioned sharp changes are characteristic for functional interdependence between water level variations in boreholes during seismic activity related to the Spitak earthquake (see Fig. 17.6). At the same time, the transition between functionally independent and dependent states are not as sharp and clear as for the Racha earthquakes. It is interesting that after the Spitak earthquake the dynamics of WL variation in different boreholes becomes more functionally dependent than before (values of mutual information increase).

The above-mentioned features of dynamics of water level variations are especially noticeable for the longest available time series. Indeed, as shown in Fig. 17.7 a and b, the dynamics of water level variability in Lisi borehole reveals a clear decrease in the extent of functional interdependence for several months before the strong earthquake. At the same time, as it was said above, some boreholes may be not sensitive to changes caused by seismic activity (King et al., 1999), e.g., water level variability in Akhalkalaki and Kobuleti boreholes does not reveal changes (Fig. 17.7 c), which can be explained by the character of regional stress field during seismic activity.

Before and during Racha and Spitak earthquakes it became possible to monitor spatial evolution of deformation processes and to define the anomalous zones relative to the background daily course of underground waters level (Figs. 17.10 and 17.11). This analysis bears information on the seismic event's approaching time. In the Racha earthquake, the compression zone anomalies are expressed by the suppression of tide effects, first of all in the boreholes located in the zone of the strongest gradient (Lisi - from 10.03. Chargali - from 05.04. Marneuli – from 08.04.) and further on boreholes located to the east, in the deformation zone with lesser gradient (from 15.04), and later on - to the east on the territory of Azerbaijan (Fig. 17.10).

Fig. 17.5 Mutual Information values calculated for 300 data length sliding windows of water level time series of pairs of boreholes: (**a**) Lisi vs. Lagodekhi, (**b**) Lisi vs. Ajameti, (**c**) Lisi vs. Akhalkalaki, (**d**) Akhalkalaki vs. Ajameti, and (e) Ajameti vs. Lagodekhi. Time of observation: 01.03.1991–30.06.1991. Sliding window at 1 hour step



The majority of data confirms the abnormal behavior of WL in boreholes on the territory of the whole Caucasian region before and after strong earthquakes. The example of regional effect is the identical behavior of boreholes Lisi and Esentuki,

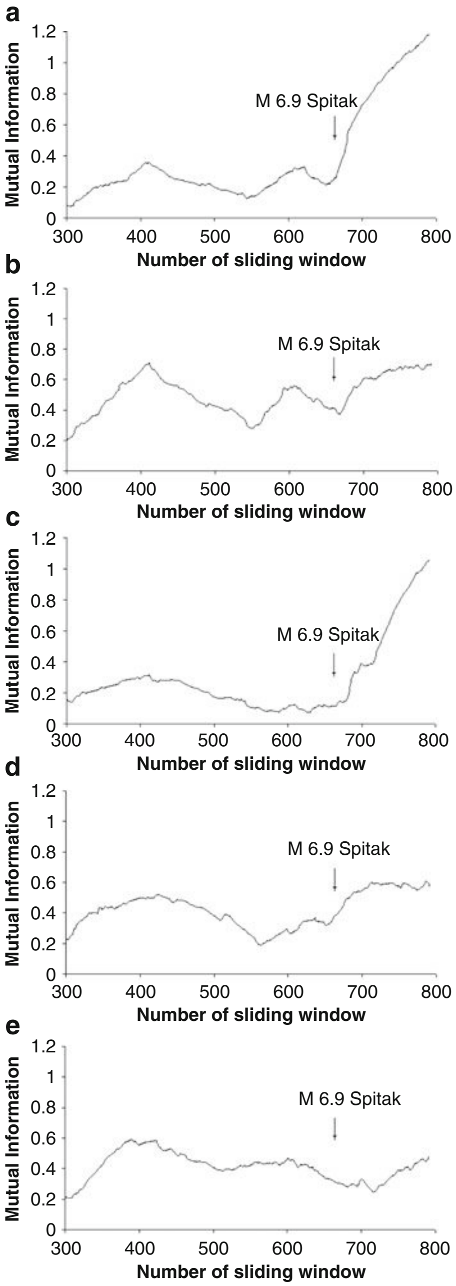


Fig. 17.6 Mutual Information values calculated for 300 data length sliding windows of water level time series of pairs of boreholes: (**a**) Lisi vs. Marneuli, (**b**) Lisi vs. Lagodekhi, (**c**) Lisi vs. Borjomi, (**c**) Lagodekhi vs. Marneuli, and (**d**) Borjomi vs. Lagodekhi. Time of observation: 11.10.1988–12.12.1988. Sliding window at 1 hour step

where compression processes adjusted the exogenous effects two months before the Racha event.

In a transitive zone (borehole Adjameti), the strong anomalies were not found. The presence of complex mosaic structure of deformation is a possible explanation

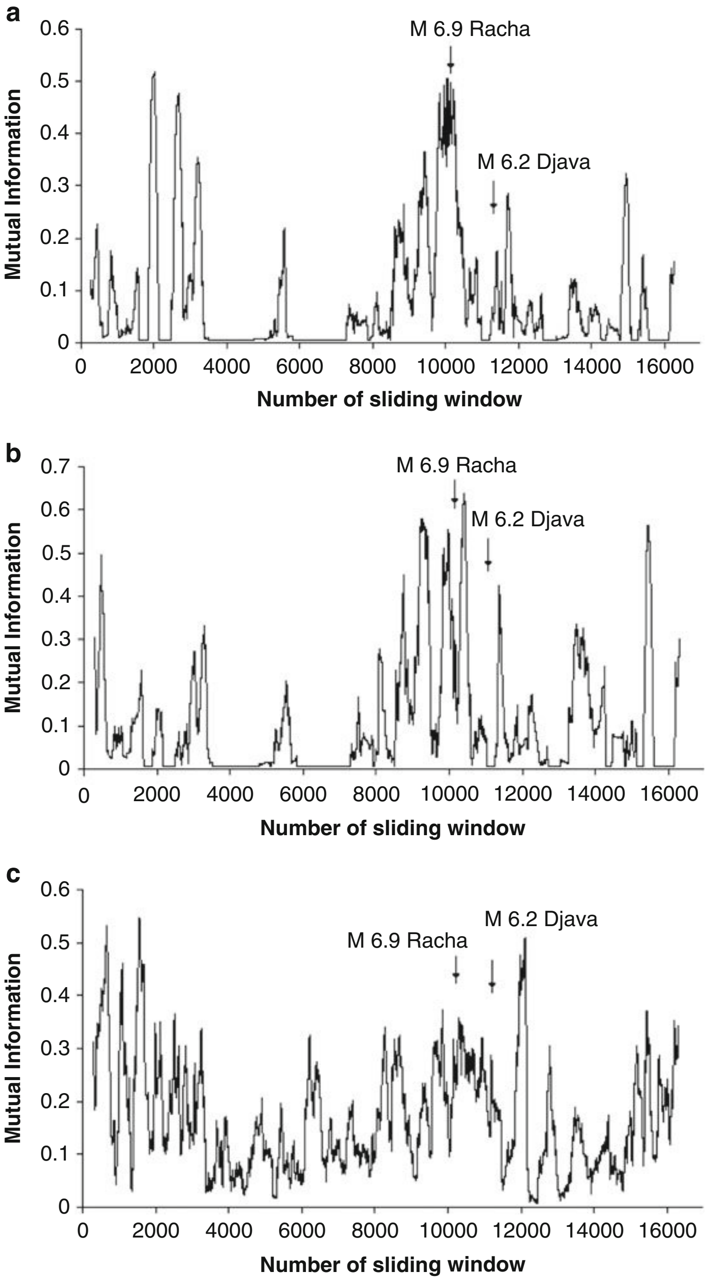
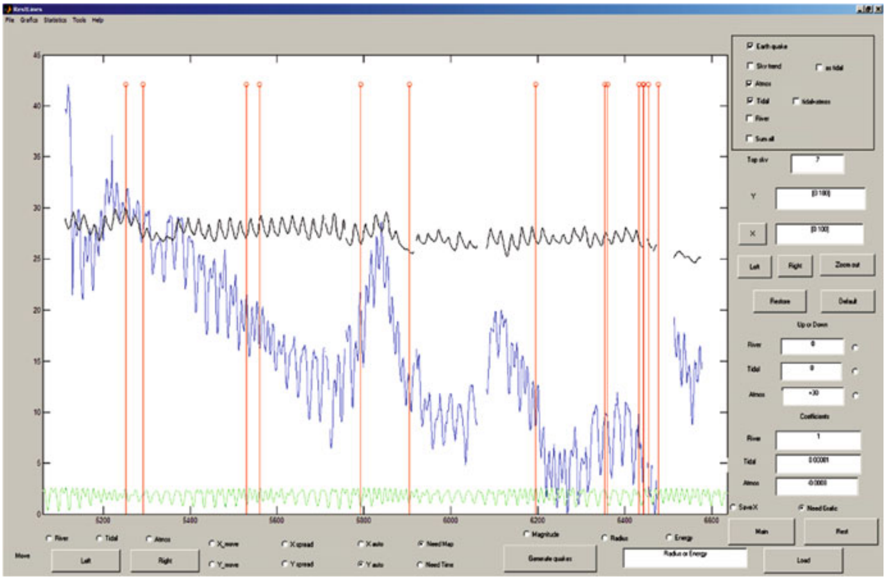


Fig. 17.7 Mutual Information values calculated for 300 data length sliding windows of water level time series of pairs of boreholes: (**a**) Lisi vs. Akhalkalaki, (**b**) Lisi vs. Kobuleti, and (**c**) Akhalkalaki vs. Kobuleti. Time of observation: 01.03.1990–29.02.1992. Sliding window at 1 hour step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Coefficients
River 1
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○ X auto ● Y auto
● Need Map ○ Need Time
○ Magnitude ○ Radius ○ Energy
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Fig. 17.8 Graph of a tidal (the bottom line), atmospheric pressure (the top line) and the underground water level (the middle line) variations in time. Vertical lines show earthquakes occurred in this period

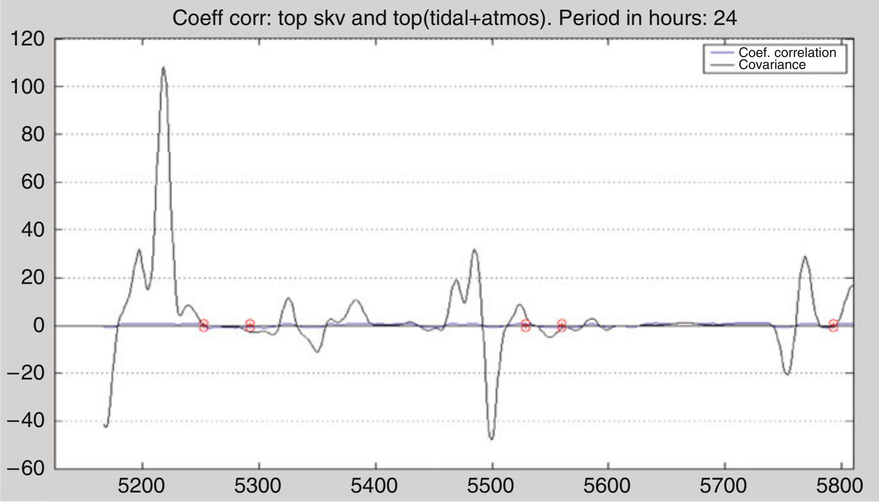

Fig. 17.9 Change of values of correlation coefficient between values of a water level and the sum of reduced values of atmospheric pressure and tidal variations

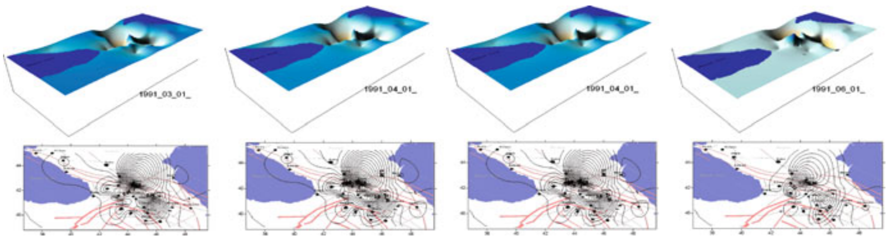

Fig. 17.10 3-D and 2-D models of evolution of stress field during preparation of the Racha earthquake of 29.04.1991 (red lines – main Caucasian faults)

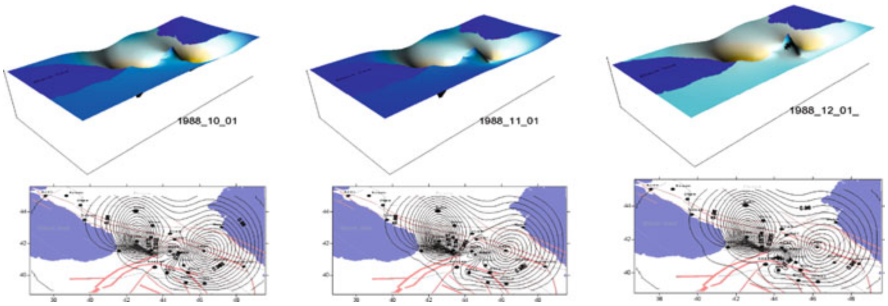

Fig. 17.11 3-D and 2-D models of evolution of stress field during preparation of the Spirak earthquake of 08.12.1988 (red lines – main Caucasian faults)

of the fact that anomaly at the borehole Oni is fixed only one month before the events - from 04.04.

In the stretching zone, the deviation from the background is marked as a weak distortion of the tide effect (borehole Adjameti from 4.04; Gali from 03.04; Sukhumi - 08.04). On boreholes Akalkalaki and Kobuleti, which are located far from the epicenter, the amplitudes of barometric fluctuation and tide effects have been gradually increasing since the beginning of March. According to the North-Caucasian data, a similar anomaly was marked on the borehole Light-blue Lakes. Such anomalies are caused by the amplification of aquifer's reaction to exogenous processes and easing of horizontal stress due to endogenous processes.

17.4 Conclusions

The dynamics of water level variability is strongly sensitive to the borehole and earthquake source location. Therefore, not all the boreholes react similarly to the changes caused by tectonic/seismic activity in the analyzed region. In sensitive boreholes, dynamical changes both before as well as after strong earthquakes are evident. When approaching time of earthquake occurrence, in most of the observed cases, the water level variability becomes more and more regular comparing to the preceding, seismically quiet time period. At the same time, the regularity in water level variability is again distorted immediately prior to the earthquake occurrence.

In spite of observations of seismicity-related dynamical changes in water level variability, there are essential qualitative and quantitative differences in the dynamics of water level variability in separate boreholes, which supposedly are strongly dependent on geological and strain field peculiarities of the considered area.

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