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Monitoring of earthquake precursors by multi-parameter stations in Eskisehir region (Turkey)

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ABSTRACT

The objective of this study was to investigate the geochemical and hydrogeological effects of earthquakes on fluids in aquifers, particularly in a seismically active area such as Eskisehir (Turkey) where the Thrace–Eskisehir Fault Zone stretches over the region. The study area is also close to the North Anatolian Fault Zone generating devastating earthquakes such as the ones experienced in 1999, reactivating the Thrace–Eskisehir Fault. In the studied area, Rn and CO_2 gas concentrations, redox potential, electrical conductivity, pH, water level, water temperature, and the climatic parameters were continuously measured in five stations for about a year. Based on the gathered data from the stations, some ambiguous anomalies in geochemical parameters and Rn concentration of groundwater were observed as precursors several days prior to an earthquake. According to the mid-term observations of this study, well-water level changes were found to be a good indicator for seismic estimations in the area, as it comprises naturally filtered anomalies reflecting only the changes due to earthquakes. Also, the results obtained from this study suggest that both the changes in well-water level and gas–water chemistry need to be interpreted together for more accurate estimations. Valid for the studied area, it can be said that shallow earthquakes with epicentral distances of <30 km from the observation stations have more influence on hydrochemical parameters of groundwater and well-water level changes. Although some hydrochemical anomalies were observed in the area, it requires further observations in order to be able to identify them as precursors.

1. Introduction

Since earthquakes are one of the most devastating natural hazards, earthquake prediction studies are continuously growing, especially in countries which have relatively greater risk. Despite the fact that countries such as the USA, China, Italy, Japan, Taiwan and Russia have been conducting research on long-term reliable and frequent enough hydrologic–hydrogeologic data for earthquake prediction (e.g. Roeloffs and Langbein, 1994; Chia et al., 2002; Aliev et al., 2003; Italiano et al., 2004; Yang et al., 2006; Itaba and Koizumi, 2007; Matsumoto et al., 2007), Turkey, unfortunately, has not been successful in establishing an effective national observation network for earthquake-induced changes. Furthermore, few studies have been conducted in Turkey for the monitoring of hydrochemical and well-water level changes related to earthquakes.

In Turkey, the first systematic attempts directed at predicting earthquakes date back to the 1999 North Anatolian Fault Zone (NAFZ) earthquakes (Simsek and Yildirim, 2000; Belin et al., 2002; Balderer et al., 2002; Gulec et al., 2002; Yalcin et al., 2003; Yaltirak et al., 2005; Yuce et al., 2007; Suer et al., 2008). One of the early investigations conducted in the studied area, was directed to establishing a connection between well-water level changes and seismic activity (Yuce and Ugurluoglu, 2003). In their study, examination of well-water level recordings obtained from 19 wells (Fig. 1) belonging to the State Hydraulic Works (DSI) showed that there were some anomalies in several wells prior to, during, and after the earthquakes.

A number of well-level changes pertaining to earthquakes have been recorded and discussed by various researchers (e.g. Igarashi and Wakita, 1992; Wakita, 1996; King et al., 1999; Gavrilenko et al., 2000; Arabelos et al. 2001; Woith et al., 2003; Koizumi et al., 2004). However, only a few studies have discussed any tectonic relationship between earthquake producing faults and the location of wells (e.g. Ekstrom et al., 1992; Roeloffs, 1996; Grecksch, 1999). These studies mention that shallow wells located in areas close to seismogenic faults are more sensitive to deformation. This is consistent with the hypothesis suggested by Yaltirak et al. (2005) that

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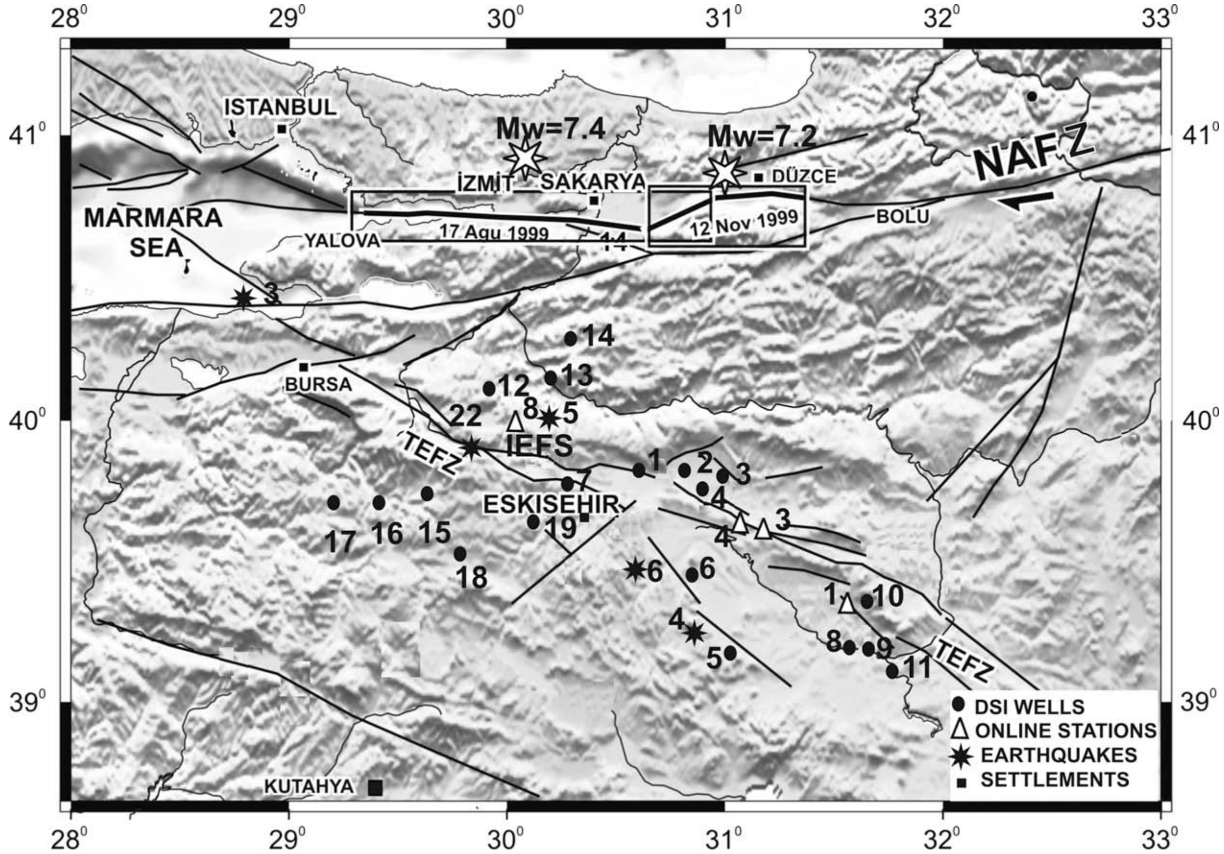

Fig. 1. Locations of the DSI wells, online-realtime stations and distribution of the earthquakes ($e \geqslant 0.35$) in the study area.

areas with young basins and older normal faults (like the Thrace–Eskisehir Fault Zone – TEFZ which have a N45°W position on the dextral E–W trending NAFZ) are subject to maximum deformation prior to earthquakes. The normal faults in the Eskisehir region have been re-activated by the NAFZ having an on the TEFZ. For that reason, the Eskisehir, Inonu and Alpu basins are ideal basins for studying pre- and post-earthquake changes in well-water level and hydrochemistry in aquifers.

The main objective of this study was to investigate the significant changes in physical and chemical properties of fluids in an aquifer by reliable and frequent monitoring. In order to achieve this aim, some chemical parameters for water (pH, EC, water temperature, redox potential, Rn and CO_2 gases) and meteorologic factors (atmospheric pressure, ambient air temperature and humidity) were monitored in five stations for about 12 months between 2006–2007 in thermal springs and water-wells (Fig. 1). It was also thought that the results obtained from this study could aid in testing the hypothesis suggested by Yaltirak et al. (2005) that "the pre-earthquake maximum strain is reached in basins bounded by stretching normal faults oriented obliquely (45°) to strike-slip faults, low activity basins developed parallel to normal faults, and basins developed on transform faults perpendicular to normal faults or thrust faults".

2. Geology, tectonics and hydrogeology

The Inonu, Eskisehir and Alpu basins are confined by faults in the south and north of the study area consisting of alluvial plains with a total surface area of 639 km^2 (Fig. 2). Pleistocene conglomerates, sands and gravels intercalated with mudstone and caliche have a thickness of about 200 m, and unconformably overlie the Miocene and pre-Neogene formations. Pleistocene sediments are overlain by 10–90 m thick Holocene alluvium that comprises loose sand and gravel of the Porsuk River. Many young normal faults are observed in the study area affected by the TEFZ (Altunel and Barka, 1998). Even though the activity of faults surrounding the Eskisehir basin is limited and some of its parts are buried by unconsolidated Miocene formations, it is possible to indicate a restricted extensional regime by the NE–SW striking dominant tectonic effect. Before the Neotectonic period, the NW–SE trending dextral strike-slip system was transformed into an extensional regime by the effects of the NAFZ during the Plio-Quaternary. It has been stated that this buried fault acted as a pure strike-slip fault before the Neotectonic period (Gozler et al., 1985).

The NAFZ, with three strands (north, middle and south), has a potential for producing devastating earthquakes such as the ones that occurred in 1999. The other fault system TEFZ angularly cuts the NAFZ. The TEFZ includes the Inonu, Eskisehir and Alpu plains. The Inonu–Eskisehir fault system (IEFS) is a part of TEFZ. IEFS is regarded as the most important active mega shear zone in the study area (Ozsayin and Dirik, 2007; Kocyigit, 2003). Several active fault segments of TEFZ are present in the area. Thus, 14 earthquakes ($M > 4$) were recorded in this region within the last century. The greatest earthquake (February 20, 1956, $M = 6.4$) in the region occured on a 10 km long WNW–ESE striking segment which was produced by the Thrace–Eskisehir Fault. Thus, the study area has a great sensitivity to the stress changes not only because of NAFZ, but also its self-producing earthquakes. Taking into account this sensitivity, monitoring stations were selected and installed near active faults. Hydrogeological conditions of the stations are given in Table 1.

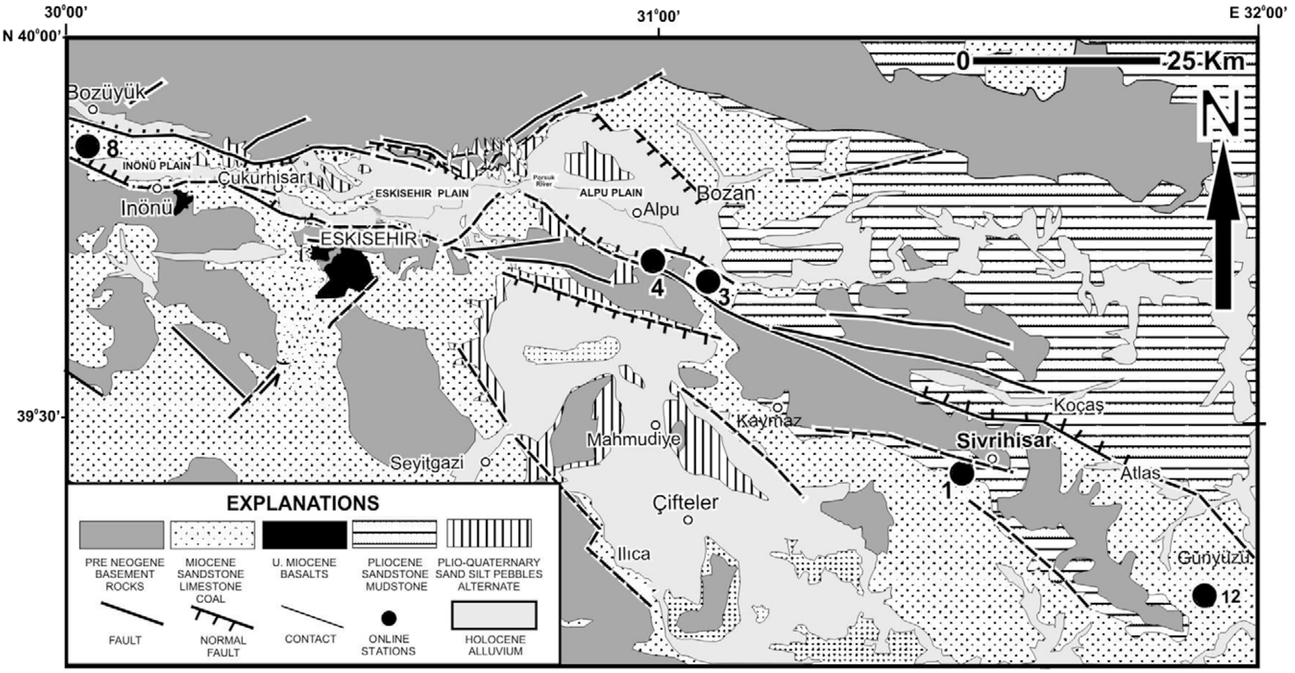

Fig. 2. Planned online and real-time station locations at the beginning of the project (modified from Yaltirak et al. (2005)) (the black circles represent the selected stations while the white ones were cancelled).

Table 1
Hydrogeologic properties of the monitoring stations in the studied area.

Online station number	Explanations	Location	Water level (m)	Depth (m)	Depth of aquifer (m)	Aquifer type	Encountered lithology in drilling	Yield (L/s)
1	DSI observation well	Sivrihisar	3	184	40–160	Confined	Conglomerate	6
3	Uyuzhamam mineral water well	Esence	Artesian	40	0–40	Confined	Alluvium	0.14
4	Uyuzhamam thermal water	Esence	–		0–100	Confined	Alluvium + melange	2
8	DSİ Observation well	İnönü-Kandilli	2	118	18–118	Confined	Alluvium	66
12	Hamamkarahisar thermal water	Sivrihisar				Confined	Alluvium + conglomerate	20

3. Material and methods

The locations of monitoring stations (online and real-time) (Fig. 2) and determination of the parameters to be measured were decided by literature search and field studies. The three main hydrogeological and geological criteria applied for the selection of these stations were: (a) locations that are sufficiently far from external effects, (b) presence of thermal water springs, (c) wells previously known to be sensitive to seismic events.

In the present study, the five monitoring stations were installed either with or without a pump. Stations using a pump were installed in Sivrihisar (No. 1), Kandilli (No. 8) and Uyuzhamam mineral water (No. 3) wells (Fig. 1). The discharge of any pump (max. 0.2 l s^{-1}) was transferred into a barrel where EC, pH, thermometer and redox potential probes were placed. The averages of 15 min measurement periods were transmitted to the recorders and then transferred to the server via modem connection. The server was equipped with an Uninterruptible Power Supply (UPS), having 30 min backup capacity, against power failure. Pumping and measurement intervals (normally set to 15 min) were configured by a Modular Environmental Data Acquisition System (MEDAS).

In stations without a pump (Uyuzhamam – No. 4 and Hamamkarahisar – No. 12 springs), water was discharged directly into a barrel and parameters such as EC, pH, redox potential, water level, water flow rate, Rn and CO_2 were measured. Radon and CO_2 gases were vacuumed from the barrel and then measured by a sensor. All the measurements were transmitted to a recorder. Also, the air temperature and indoor/outdoor humidities were measured in order to be able to eliminate possible noise effects.

Data transfer to a computer was done by the MEDAS program. The raw data from MEDAS were then loaded to an earthquake-monitoring program. The MEDAS program was configured before the data transfer. Following the configuration, the recorded data in mV was converted into pertinent units. In the case of a possible power failure, the recorded data were labeled by using recording time.

During the evaluation period of the data, to prevent misinterpretation, a few data gaps due to power failures were completed by interpolation using a macro program. This macro program accomplished the completing procedure in two steps. In the first step, a time slice of 15 min was added. In the second step, each time slice was completed by interpolation using the adjacent measured values. The data obtained by this procedure were plotted using MS Excel at the early stages of the study. However, the size of the recorded data and 3D data sets (time-earthquake-measured parameter) caused difficulties in plotting. Therefore, to overcome these difficulties, software named "EQ" was developed for the graphical presentation of data sets.

The earthquake activity function "*e*" was calculated by taking into account that function is proportional to the areal change of energy (Hartman and Levy, 2006). The effect of each earthquake to each monitoring station was calculated by a macro program using

Table 2
Selected earthquakes with $e \geqslant 3.5$ (in bold).

EQ No.	Event time	Lat.	Long.	Depth (km)	Magnt. (M)	Name of the earthquake	Calculated (*e*) values for each stations			
							Sivrihisar station No. 1	Kandilli station No. 8	Uyuzhamam thermal water station No. 4	Uyuzhamam mineral water station No. 3
1	23.08.2006 06:25	39.04	31.83	5.4	3.1	Celtik (Konya)	0.41	0.04	0.12	0.12
2	15.10.2006 08:05	38.76	31.60	5.0	3.7	Yunak (Konya)	0.92	0.15	0.39	0.40
3	**24.10.2006 17:00**	**40.42**	**28.99**	**14.3**	**5.2**	**Gemlik Bay**	2.35	1.16	3.54	**3.46**
4	**29.10.2006 04:15**	**39.35**	**31.09**	**12.1**	**3.3**	**Cifteler (Eskisehir)**	1.50	0.17	1.44	**1.54**
5	**20.11.2006 11:57**	**39.88**	**30.66**	**18.3**	**3.0**	**Hekimdağ (Eskisehir)**	0.12	**0.36**	0.57	0.51
6	**04.12.2006 12:11**	**39.58**	**30.65**	**10.5**	**3.1**	**Seyitgazi (Eskisehir)**	0.20	**0.37**	**0.83**	0.76
7	12.11.2006 04:36	40.14	32.70	4.8	4.4	Kazan (Ankara)	1.26	0.40	0.90	0.92
8	14.12.2006 21:43	38.97	31.65	5.1	3.0	Celtik (Konya)	0.35	0.03	0.11	0.11
9	12.12.2006 06:16	39.01	31.39	5.4	3.4	Celtik (Konya)	0.97	0.08	0.27	0.28
10	12.12.2006 06:37	38.95	31.69	4.9	3.1	Celtik (Konya)	0.39	0.04	0.12	0.13
11	12.12.2006 07:23	38.93	31.70	5.6	3.1	Celtik (Konya)	0.37	0.04	0.12	0.12
12	07.01.2007 14:23	38.97	31.67	15.7	3.0	Celtik (Konya)	0.34	0.03	0.10	0.11
13	23.01.2007 23:21	38.11	28.73	5.0	4.5	Buldan (Denizli)	0.35	0.61	0.40	0.40
14	30.03.2007 19:56	38.00	30.93	6.6	4.7	Eğirdir (Isparta)	1.88	1.11	1.50	1.51
15	30.03.2007 22:23	37.99	30.92	5.9	4.7	Eğirdir (Isparta)	0.03	1.11	0.02	1.50
16	31.03.2007 04:20	38.17	30.97	9.2	4.1	Gelendost (Isparta)	0.61	0.33	0.47	0.47
17	11.04.2007 00:39	38.01	30.95	6.7	4.6	Gelendost (Isparta)	1.54	0.89	1.21	1.23
18	11.04.2007 01:00	38.00	30.93	8.1	4.9	Eğirdir (Isparta)	3.00	1.76	2.39	2.41
19	11.04.2007 11:59	38.02	30.91	23.2	4.3	Eğirdir (Isparta)	0.77	0.46	0.62	0.62
20	11.04.2007 12:57	38.05	30.92	3.6	4.2	Gelendost (Isparta)	0.63	0.37	0.50	0.51
21	11.04.2007 13:06	38.04	30.91	5.0	4.3	Gelendost (Isparta)	0.78	0.46	0.62	0.63
22	**04.04.2007 18:33**	**39.87**	**29.94**	**8.9**	**2.9**	**Dodurga (Bozüyük)**	0.03	**1.92**	0.07	0.07
23	19.04.2007 16:21	38.58	31.24	8.2	4.0	Sultandağı (Afyon)	1.12	0.33	0.68	0.70

Table 3
Correlative data of the various parameters obtained from monitoring stations during aseismic and seismic periods.

Online station No.	Time interval	EQ No.	R^2	(*e*)	Normal response	Abnormal response	Probable anomaly
8	19 October–9 November 2006	4	0.10	**0.36**	EC↑ BP↑	EC↑ BP↓	–
8	25 March–14 April 2007	22	**0.13**	**1.92**	EC↑ BP↑	EC↑ BP↓	+
8	28 December 2006–17 January 2007	12	0.32	0.03	EC↑ BP↑	EC↑ BP↓	–
8	10 November 2006–30 November 2006	5	**0.13**	**0.36**	EC↑ BP↑	EC↑ BP↓	+
8	9–29 April 2007	23	0.06	0.33	EC↑ BP↑	EC↑ BP↓	–
8	25 November 2006–14 December 2006	6	**0.15**	**0.37**	CO_2↑ Rn↓	CO_2↑ Rn↑	+
8	13 August 2006–2 September 2006	1	0.57	0.04	CO_2↑ BP↓	CO_2↑ BP↑	–
1	9–29 April 2007	23	0.05	1.12	Water temp.↑ redox↓	Water temp.↑ redox↑	–
1	26 March 2007–14 April 2007	22	0.21	0.03	CO_2↑ BP↓	CO_2↑ BP↑	ND
3	5–25 October 2006	2	0.21	0.4	pH↑ water temp.↓	pH↑ water temp.↑	No relation
3	19 October 2006–9 November 2006	4	**0.40**	**1.54**	EC↑ BP↑	EC↑ BP↓	+
3	14 October 2006–4 November 2006	3	**0.38**	**3.46**	EC↑ BP↑	EC↑ BP↓	+
3	2 December 2006–22 December 2006	9, 10, 11	0.11	0.28	EC↑ BP↑	EC↑ BP↓	–
3	2 December 2006–22 December 2006	9, 10, 11	0.15	0.28	Water temp.↑ Rn↑	Water temp.↑ Rn↓	–
3	13 August 2006–2 September 2006	1	0.11	0.12	Rn↑ BP↓	Rn↑ BP↑	–
4	2 December 2006–22 December 2006	9, 10,11	0.08	0.27	EC↑ water temp.↑	EC↑ water temp.↓	–
4	25 November 2006–14 December 2006	6	0.20	0.83	EC↑ CO_2↑	EC↑ CO_2↓	ND
4	10 November 2006–30 November 2006	5	0.97	0.57	EC↑ Rn↑	EC↑ Rn↓	ND
4	25 November 2006–14 December 2006	6	**0.24**	**0.83**	Water temp.↑ redox↓	Water temp.↑ redox↑	+
4	2 December 2006–22 December 2006	9, 10,11	0.13	0.27	Water temp.↑ redox ↓	Water temp.↑ redox↑	–
4	2 December 2006–22 December 2006	9, 10, 11	0.005	0.27	Water temp.↑ radon↑	Water temp.↑ radon↑	–

the equation $10^M/D^2$ where D is the epicentral distance to Eskisehir within a 500 km radius and M is the earthquake magnitude. The calculated "*e*" values >0.35 were taken into account (this threshold value was selected as 0.20 in Hartman and Levy (2006)). Table 2 gives the pertinent earthquakes selected by using this threshold value of 0.35 and by considering the regional tectonics in related basins. Thus, special attention was paid to the selection of earthquakes. Accordingly, although a total of 23 earthquakes were determined within a radius of 500 km (Table 2), only the earthquakes generated by the TEFZ and having "*e*" values higher than 0.35 were considered. These selected earthquakes are shown in Fig. 1.

The data obtained by above mentioned procedure were separated into time intervals chosen to be 10 days before and 10 days after each earthquake. Then, each couple of parameters was correlated into a 20-day interval. The aseismic and seismic periods were acquired by considering a meaningful determination coefficient as $R^2 \geqslant 0.13$ (Hartman and Levy, 2006). When an earthquake activity function "*e*" was smaller than 0.35, this period was considered as "aseismic." Fig. 1 shows the distribution of selected earthquakes with respect to observation stations. The calculated R^2, earthquake number, and changes in observed parameters are given in Table 3. In this table, arrows (↑) and (↓) denote increase and decrease, respectively. Considering the correlations of each parameter, the discrepancies of parameters during aseismic and seismic periods are also given in Table 3.

4. Results and discussion

The obtained results based on the measured parameter-couples in the present study can be generalized as explained below. Also,

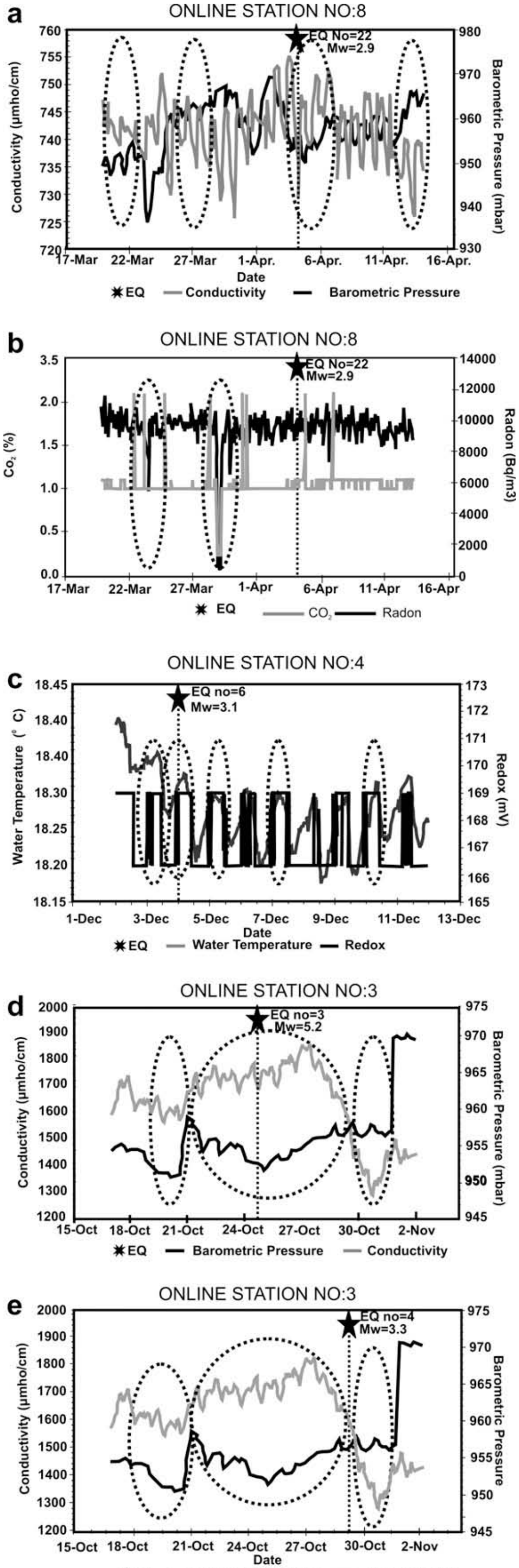

Fig. 3. Probable anomalies (in circles) recorded at four study sites during 2006: (a) barometric pressure (BP) vs. EC plot of Kandilli monitoring station (No. 8), probably associated with the No. 22 earthquake, (b) Radon vs. CO_2 plot of Kandilli monitoring station (No. 8), probably associated with the No. 22 earthquake, (c) water temperature vs. redox potential plot of Uyuzhamam (thermal water) monitoring station (No. 4), probably associated with the No. 6 earthquake, (d) barometric pressure vs. EC plot of Uyuzhamam (mineral water) monitoring station (No. 3), probably associated with the No. 3 earthquake, (e) barometric pressure vs. EC plot of Uyuzhamam (mineral water) monitoring station (No. 3), probably associated with the No. 4 earthquake.

Table 4
Probable anomaly indicating parameter-couples.

Online monitoring station No.	EQ No.	Name of the earthquake	Time interval	Parameters	Epicentral distance (km)	Focal depth (km)
8	22	Dodurga (Bozüyük)	25 March 2007–13 April 2007	EC–BP	16.5	8.9
8	5	Hekimdağ	10–30 November 2006	EC–BP	52.8	18.3
8	6	Seyitgazi	25 November 2006–14 December 2006	CO_2–Rn	58.4	10.5
4	6	Seyitgazi	2–12 December 2006	Water temp.–Redox	38.8	10.5
3	3	Gemlik Bay	14 October 2006–31 October 2006	EC–BP	213.9	14.3
3	4	Çifteler	19 October 2006–9 November 2006	EC–BP	36.0	12.1

Table 5
Well-water level changes before and after the earthquakes.

DSI observation well (No.)	EQ No.	Name of the EQs	EQ event date	Magnitude of the EQs	General trends in well-water levels changes for 1 month before and after the earthquakes Nos. 5 and 6	Instant behavior of water level in a short period related with the earthquakes Nos. 5 and 6	Well-water level changes (mm)				Probable indication of an anomaly
							Drop	Rise	Starting date	Ending date	
Bozan (3)	5	Hekimdağ	20.11.2006	3.0	Continuous increase	Decrease	150		13.11.2006	17.11.2006	Yes
Osmaniye (2)	5	Hekimdağ	20.11.2006	3.0	Continuous increase	Decrease	30		23.11.2006	28.11.2006	Yes
Yenikent (7)	6	Seyitgazi	04.12.2006	3.1	Constant	Gradual increase		800	23.11.2006	31.12.2006	Yes

these results are in a good agreement with the observations made by Zmazek et al. (2002) and Walia et al. (2005) for the different areas:

- When there is upwelling from the deep aquifer towards the shallow one, the water level and CO_2 concentration increase in the shallow aquifer even during the dry period.
- An increase in humidity and decrease in EC due to dilution can be seen in the wet period.
- Barometric pressure oscillates during the day, generally increasing in the morning and decreasing in the noon.
- There is an inverse relationship between barometric pressure and water level.
- Radon concentration decreases during rainfall due to a dilution effect.
- Radon concentration increases due to increasing molecular activity when there is an increase in heat originating from the deep aquifer.
- Redox potential decreases with an increase in electrical conductivity (EC).
- An increase in redox potential indicates O_2 input from fresh water, and hence pH increases.
- A decreasing redox potential indicates CO_2 input, and hence pH decreases.
- EC increases with increasing water temperature.
- Whenever the ambient air temperature increases, humidity decreases but barometric pressure increases.
- Radon concentration decreases with increasing barometric pressure.
- Barometric pressure and EC decrease during rainfall.

The station-specific details based on the correlations between the parameter-couples are as follows:

4.1. The Sivrihisar monitoring station (No. 1)

Even though there was a meaningful determination coefficient between water temperature and redox potential related with the No. 23 Sultandag earthquakes, the changes in water temperature by 0.1 °C and 0.250 μS/cm in EC were not regarded as an important anomaly. High correlation coefficients were found between CO_2 concentration-barometric pressure and CO_2 concentration–humidity during the Dodurga earthquake (No. 22) (observation period between 26 March and 14 April 2006). However, the latter was not considered due to a malfunction of CO_2 and humidity sensors within this period.

4.2. The Kandilli (Inonu) monitoring station (No. 8)

Abnormal behavior was observed between EC and barometric pressure (BP) during 19 October and 9 November during Cifteler earthquake (No. 4). Normally, a decrease in barometric pressure was followed by a decrease in EC, as expected. However, such behavior was not observed during Dodurga–Bozüyük earthquake (No. 22) (Fig. 3a). On the other hand, CO_2 and Rn changed with inversely to contrary of normal behavior possibly due to the same earthquake (No. 22) (Fig. 3b).

4.3. The Uyuzhamam (thermal water) monitoring station (No. 4)

Abnormal behavior between EC and water temperature was observed during Celtik earthquakes (Nos. 9, 10 and 11). Although high correlations were obtained between EC and Rn for a short period before the Seyitgazi earthquake (No. 6) (25–28 November 2006) and during the Hekimdag earthquake (No. 5) (10–30 November 2006) between EC and CO_2, they were not evaluated due to malfunction of sensors. Covering the examination period of the Seyitgazi earthquake (No. 6) (2–12 December 2006), the relationship between water temperature and redox was observed as abnormal (Fig. 3c). The relationship recorded between water temperature and Rn was not taken into account due to the low water temperature changes during the same period. Thus, water temperature and redox potential changed inversely with respect to the normal which might be evaluated as an anomaly.

4.4. The Uyuzhamam (cold mineral water well) monitoring station (No. 3)

Relatively high determination coefficients were obtained between barometric pressure and EC during Gemlik (No. 3) and Cifteler (No. 4) earthquakes (Fig. 3d and e). These results may also be considered as an anomaly related with earthquake.

Unfortunately, the last monitoring station, Hamamkarahisar thermal spring was abandoned due to scaling problems which blocking water flow circulation within the system.

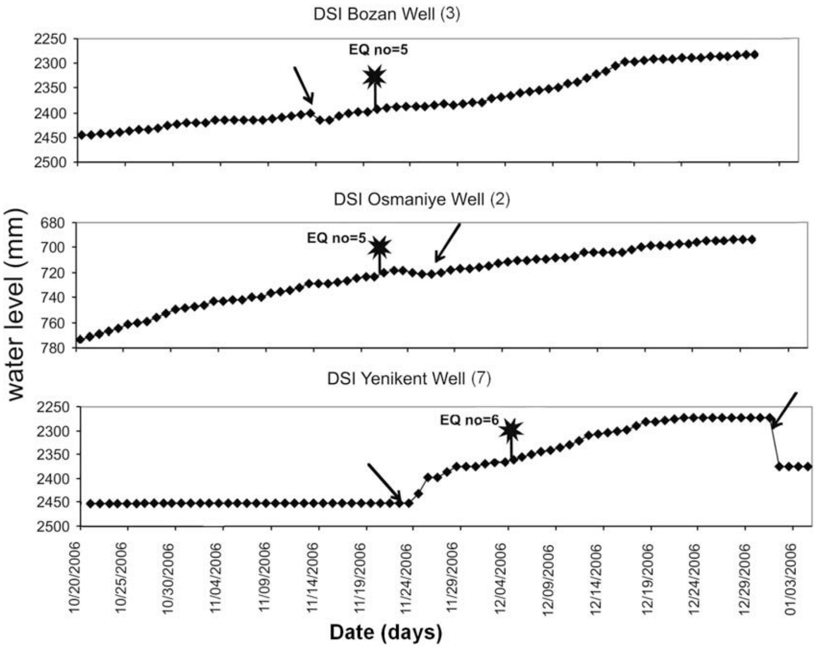

Fig. 4. Well-water level anomalies observed in DSI wells related to earthquakes Nos. 5 and 6.

The obtained results are summarized in Table 4 by evaluating all the above-discussed probable anomalies. It can be inferred that the effective radius of epicentral distance is less than 30 km with earthquakes $M < 3.3$. This seems to have more influence on hydrochemical changes in the monitoring stations. Since the Gemlik earthquake (No. 3) was the only earthquake with $M > 5$ during whole observation period (August 2006–May 2007), it was out of the consideration due to a unique case.

The relationship between well-water level changes and hydrochemical changes possibly occured due to the earthquakes was examined. The background and recent trends of well-water level changes (obtained from the limnigraph data of DSI wells) one month before and after the earthquakes were also studied and presented in Table 5. On the basis of the evaluation of all recorded data, it can be concluded that similar anomalies in hydrochemical parameters to that of the earthquakes (Nos. 5 and 6) are present for the well-water level changes in the wells. The discrepancy between the general and instant behavior in the well-water levels can be followed in Table 5. It is obvious that, during the seismic period, well-water levels either drop (Nos. 2 and 3 of DSI wells) or rise (No. 7 DSI well), which can be accepted as possible precursories of the earthquakes (Fig. 4).

Furthermore, the epicentral distances of the earthquakes to the DSI wells are consistent with previous results which were given in Table 4. The focal depths of earthquakes Nos. 5 and 6 are about 10–18 km, respectively. Thus, the hydrochemical anomalies, considered to be due to these earthquakes with epicentral distances of 16.5–58.4 km from earthquakes Nos. 5 and 6 were also observed in the water level anomalies in the DSI wells that are approximately 20–30 km from the same earthquakes.

5. Conclusions

Earthquake-induced changes in well-water levels and hydrochemistry of groundwater were studied in the Eskisehir region by online-realtime monitoring stations and DSI limnigraphed wells. The changes of water level in the DSI wells a few weeks prior to some earthquakes can be accepted as precursory. The recordings obtained from the Bozan well can be accepted as a remarkable indicator of such a precursory.

It was observed that changes occurred in EC, CO_2, Rn, water temperature and redox values of the groundwaters in the online-realtime monitoring stations with the epicentral distances of 16.5–58.4 km from the four earthquakes (except the Gemlik earthquake) with magnitudes of 2.9–3.3 and focal depths of 8.9 and 18.3 km. Similar changes also occurred in the water levels of DSI observation wells approximately 20–30 km far from the epicenters of earthquakes Nos. 4 and 5. Although some hydrochemical anomalies were observed in the studied area, further observations and recurrence of similar anomalies are necessary in order to be able to identify them as precursors. It can be stated that earthquakes with epicenteral distances less than 30 km to the observation stations have more influence on hydrochemical parameters of groundwater and well-water level changes for the Eskisehir region.

The wells located in the Eskisehir basin showed signs of anomalies prior to nearby earthquakes of $M < 5$. However, the question of whether these well-level changes could be evaluated as a precursor of a possible earthquake could not be answered satisfactorily since it was not possible to record any earthquake with a magnitude of $\geqslant 5$. In addition, it was not possible to test the tectonic model proposed by Yaltirak et al. (2005) which is "the stress reaches to a maximum value prior to earthquake in low activity basins having a 45° angle with active strike-slip faults" due to lack of earthquake recordings with a magnitude of $M \geqslant 5$ in the vicinity of the studied area.

As a conclusion, earthquake-induced changes in well-water level and hydrochemical parameters seem to be more sensitive for the short epicentral and hypocentral distances to the monitoring stations. Of course, further studies are required to confirm the main conclusions arrived at in the present study.

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