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ANALYSIS OF FACTORS FORMING THE GROUNDWATER REGIME IN THE WEST BOHEMIAN SEISMOACTIVE REGION

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ABSTRACT
Groundwater levels began to be monitored in three hydrogeological wells in the seismoactive region of Western Bohemia in June 2000. The main purpose of the monitoring was to observe the effects of seismicity on the groundwater regime. The fluctuation of the groundwater level in particular wells is influenced by precipitation, air pressure changes and earth tides. All the three observed wells were subjected to tidal analysis of the measured groundwater levels, in order to determine their sensitivity to crustal strain. Anomalies related to seismic activity were observed during the August – December 2000 swarm in the NK 2 well, which is situated in the epicentral area of Nový Kostel.

KEYWORDS: West Bohemian seismoactive region, groundwater level fluctuations, August - December 2000 swarm, tidal analysis, hydrogeological effects of earthquakes

1. INTRODUCTION

The intraplate seismoactive region of the north-western marginal part of the Bohemian Massif includes the territory of Western Bohemia, approximately delimited by the towns of Kraslice, Aš, Cheb, Lázně Kynžvart and Sokolov, the adjoining territory of Saxony in the wider neighbourhood of Plauen and the vicinity of Marktredwitz in north-eastern Bavaria. The total area of the region is about 1000 km^2. It is characterized by high seismicity with low magnitudes (M<5), in particular, by the occurrence of earthquake swarms, which are monitored by a dense network of local stations. Thousands of tremors were recorded during some of these swarms. In the past century, such swarms occurred in the years 1901, 1903, 1908, 1911, 1929, 1936, 1962, 1973, 1985/1986 and 2000. One of the strongest swarms, which occurred during December 1985 and January 1986, consisted of more than 8000 events. The macroseismic effects of the two strongest events with local magnitudes $M_l = 4.6$ and $M_l = 4.1$ reached 7° and 6°, respectively, on the MSK-64 scale (Procházková et al., 1987). Over the past 20 years, the area of Nový Kostel has been the most active zone. The probable cause of earthquake swarms is the local weakening and inhomogeneity of the Earth's crust, and probably also other processes such as post-volcanic activity and the incidence of fluid systems in the crust (cf., e.g., Bankwitz et al., 2003; Heinicke and Koch, 2000). The activity of fluid systems results in surface gas seepages and in the outflow of mineral springs.

In addition to monitoring of seismic activity, the Institute of Rock Structure and Mechanics AS CR launched the monitoring of groundwater levels in three observation wells in June 2000. Two wells are situated in the epicentral area of Nový Kostel; the third one was sunk at the south margin of the Slavkov crystalline, near the municipality of Krásno. The ultimate purpose of the measurements is observing earthquake-induced groundwater level changes.

Groundwater level fluctuations are induced not only by hydrological and meteorological factors, but also by deformations acting in the Earth's crust. The main non-anthropogenic factors causing the deformations of aquifers are tidal forces and changes of stress-strain conditions before, during or after earthquakes. Tidal effects on the groundwater regime are frequently documented and extensive data collections from all over the world are available, which enables the tidal effects on various hydro-geological structures to be compared (cf., e.g., Melchior, 1983, Ljubušin et al., 1997; Hobbs and Fourie, 2000). There are also many reports on hydrogeological effects of earthquakes from different seismoactive regions of the world (cf., e.g., Kissin, 1982; Roeloffs, 1988; Montgomery and Manga, 2003). Not only strong earthquakes induce ground-water regime anomalies. For example, Kissin et al. (1996) reported cases, where the co-seismic or postseismic well level changes were induced by seismic events with magnitudes M < 2. In the West Bohemian seismoactive region distinct changes of mineral spring yield were detected during the strong earthquake swarm in 1985 and 1986 (Novotný and Matyska, 1989). In the following years the groundwater regime changes related to seismic activity were detected especially at German localities (cf. Koch et al., 2003; Weise et al., 2001).

This paper summarizes the results of groundwater monitoring carried out during the period June 2000 – December 2004 and deals with an assessment of the effects of various factors involving the groundwater regime, including the seismic activity.

2. GEOLOGY OF OBSERVED LOCALITIES

2.1. *NOVÝ KOSTEL*

The Nový Kostel area is situated at the western margin of the Svatava crystalline, which is a part of the Krušné hory (Erzgebirge) unit (cf. Fig. 1). The crystalline complex is divided by the Krušné hory fault into two blocks. The northern – so called Oloví block is composed predominantly of mica schists and phyllites. The lithology of the southern, Kynšperk block is a little more complicated. It consists of quartzites, mica schists and phyllites. In its eastern part is the Kynšperk block covered by Tertiary deposits of the Sokolov basin. To the south is the Svatava crystalline bounded by the Eger fault and the Sokolov fault, to the west it is separated from Tertiary deposits by the Mariánské Lázně (Marienbad) fault. The NK 1 and NK 2 wells were drilled to a depth of 23 m in the close neighbourhood of the northern part of the Mariánské Lázně fault, approximately 2 km north of the municipality of Nový Kostel. Both wells pass through the weathered zone and end in the two-mica schists of the Oloví block. They are situated on the slope above the local drainage base, which is represented by the valley of the left-hand side tributary of the Lubinka brook. The valley is fixed to the Mariánské Lázně fault. The difference in altitude of the NK1 and NK 2 wellheads is 64 m, the horizontal distance between the two wells is 480 m. The observed aquifer is the zone of surface loosening of two-mica schists. Aquifer tapped by the NK 2 well is confined.

2.2. *KRÁSNO*

The Krásno area is situated at the southern margin of the Slavkov crystalline (Fig. 1). This crystalline complex has a dome structure and is divided into two parts – the older and intensively metamorphosed core (Slavkov orthogneisses) and the younger weakly metamorphosed cover series. Silimanite-biotite- and two-mica paragneises and mica schists with quartzites prevail in the composition of the cover series. Various types of Hercynian granites penetrate the whole crystalline complex. To the north the Slavkov crystalline adjoins the Kynšperk block of the Svatava crystalline. Both structural units are divided by the Sokolov fault. The marginal parts of the Slavkov crystalline are disrupted by longitudinal faults (running NE-SW) to the south and by transverse faults (running NW-SE) to the south-east, in the neighbourhood of Horní Slavkov and Krásno. The HM 1 well was sunk in the orthogneisses of the core of the Slavkov crystalline. The depth of the well is 23 m and it follows an unconfined aquifer in the surface zone of a fissure disjunction.

3. METHODS OF GROUNDWATER MONITORING

Pressure sensors DCP-PLI03 produced by DataCon Co. Ltd., Prague, are used for recording the groundwater level and temperature. The sensors are connected to digital data loggers with a capacity of 32 000 measured values. The data (an average of 5 measured values) were recorded with a sampling period of 3 minutes until March 2004. After a short interruption of monitoring, the sampling period was set to 6 min in May 2004. The accuracy of the measured values is 0.1% with the immersion depth of the sensor amounting to 10 metres. Deduction step is 1 mm. The accuracy of the thermal sensor is 0.3 °C in the temperature range 0 – 50 °C.

4. RESULTS OF MONITORING

4.1. *NOVÝ KOSTEL NK 1 AND NK 2*

The groundwater level fluctuations in both wells are very similar (Fig. 2). The only significant difference is the relatively frequent groundwater offtake, which causes abrupt non-periodic changes of the NK 2 well level record. The groundwater is withdrawn from another domestic well, which is situated approximately 10 m from the NK 2 well. Both wells display typical seasonal variations affected by precipitation and the melting snow. The comparison of the seasonal variations of the NK 1 and NK 2 groundwater levels displays a noticeable phase difference in the local absolute maxima and minima, which always occur earlier in the NK 1 well. The differences between the minimum and maximum groundwater levels in the NK 1 and NK 2 wells during the whole period of monitoring were 3.29 m and 6.18 m, respectively. The NK 2 level was higher than the NK 1 level during most of the observed period.

4.2. *KRÁSNO HM 1*

From the December 2000, the groundwater level of the HM 1 well displayed a noticeable upward trend, which lasted until the spring of 2003. During the extremely dry year of 2003, the groundwater level dropped considerably and the previous trend was discontinued. Towards the end of the year 2004 the groundwater rose to a level, which is approximately 2.2 m lower than the level before the decrease of summer-autumn 2003 (Fig. 2). The difference

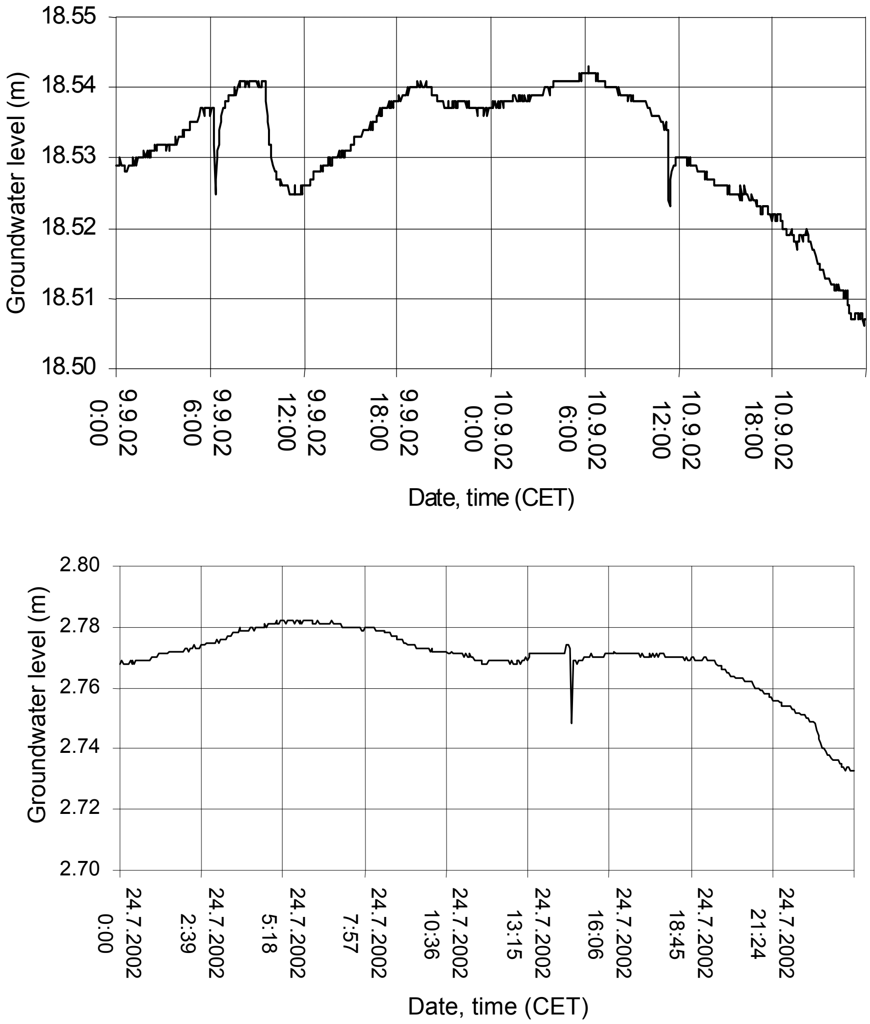

Fig. 3 Transient short-time anomalies, recorded in September 2002 in HM 1 well.

between the minimum and maximum level during the whole period of monitoring was 4.38 m.

The anomalous behaviour of the groundwater level was observed from April to September 2002. During this period were recorded several abrupt anomalies with a duration of several minutes and oscillations of the groundwater level of up to 20 mm. These fluctuations (Fig. 3) show no time coincidence, either with seismic events, or with blasts in the nearby quarry. One can assume that only sudden short-term changes of atmospheric pressure were the cause of these oscillations. The air pressure values measured with the appropriate frequency are not available. The effects of air pressure changes on the groundwater level are discussed below.

4.3. GROUNDWATER TEMPERATURE VARIATIONS

The seasonal fluctuations of groundwater temperature in the observation wells display relatively low values, which sometimes only slightly exceed the declared instrumental accuracy of 0.3 °C (cf. temperature changes in the HM 1 well during the period from June 2000 to August 2001 and during the year 2004 in Fig. 4c). Usually the seasonal changes of groundwater temperature range from 2 °C to 2.5 °C. The temperature minimum occurs during the spring, when the groundwater is cooled due to aquifer replenishment with melting snow. The spring temperature drop is regularly followed by a gradual increase, until the beginning of winter.

5. FACTORS INVOLVING THE GROUNDWATER REGIME

The groundwater regime, which includes spatial and temporal changes of water dynamics and chemical composition, is the result of the influence of several factors, which act continuously (e.g., air pressure and temperature, earth tides) or only episodically (e.g., precipitation or earthquakes). Some of these factors have a periodic time distribution, which is then a)

b)

c)

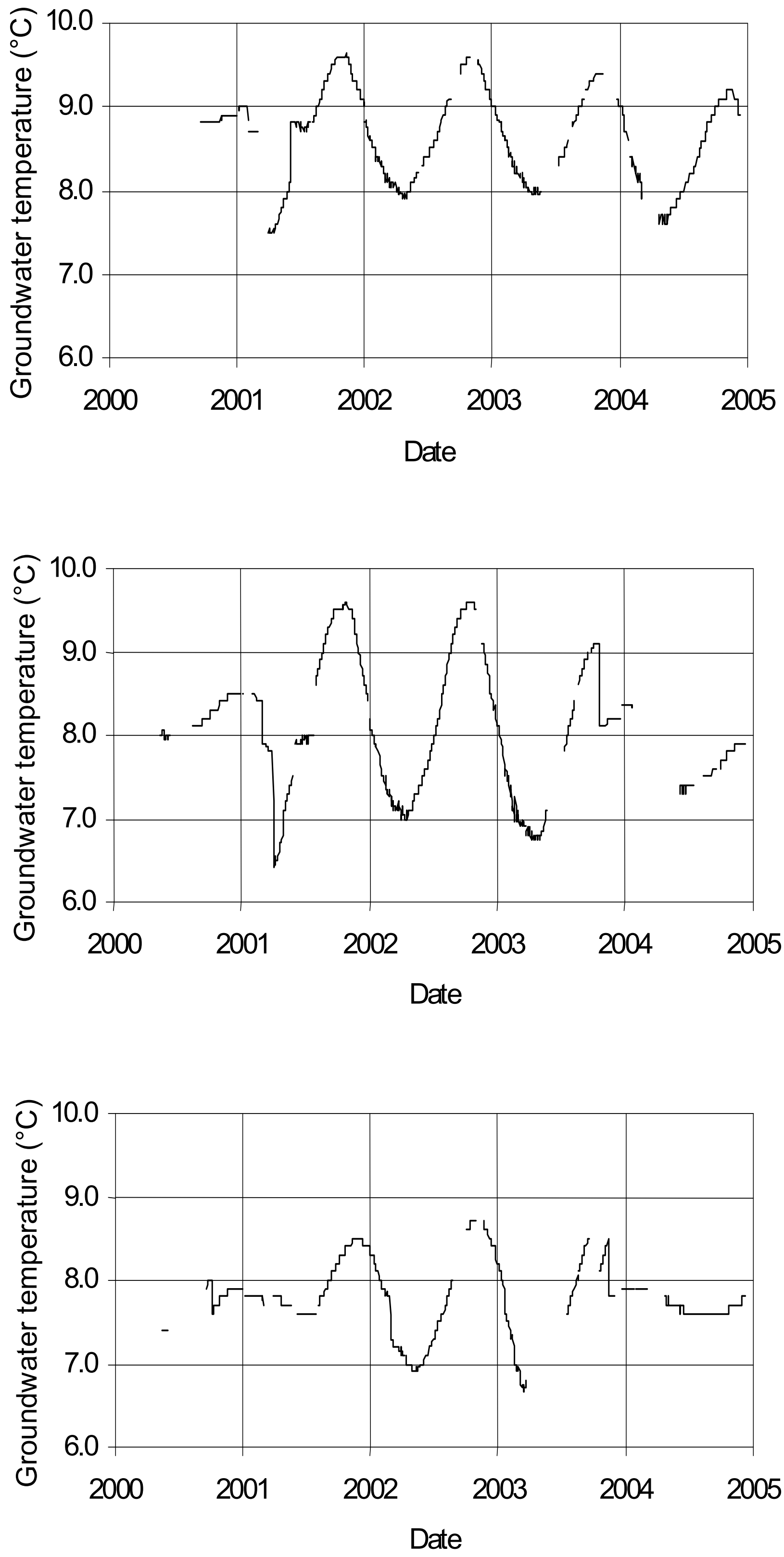

Fig. 4 Groundwater temperature fluctuations: a) NK 1 well, b) NK 2 well, c) HM 1 well

reflected in the variation of particular groundwater regime parameters. But in general, these parameters do not show only a periodic fluctuation and their time variation is considerably more complicated. Three basic types of groundwater level fluctuations were identified in all the three observation wells:

1. Seasonal fluctuations corresponding to seasonal aquifer replenishment due to precipitation and snow cover melting.
2. Periodic diurnal and semidiurnal fluctuations related to tidal effects.
3. Stochastic fluctuations induced by air pressure changes, anthropogenic effects, or by earthquakes.

5.1. PRECIPITATION

Precipitation amounts are reflected in the groundwater levels of all the three monitored wells. The most distinct correlations are observed in the NK 1 and NK 2 wells; where contrary to the HM 1 well such distinct long-term trends do not occur (Fig. 2). The groundwater level displays no correlation with any particular precipitation events. This is generally considered as a common feature, when observing groundwater level fluctuations. The groundwater level is always observed to rise with a certain delay after precipitation occurs. Moreover during the summer months, when the precipitation maximum regularly occurs, the aquifer's replenishment in temperate climatic conditions practically stops (Kříž, 1996). In summer most of the precipitation is intercepted in the uppermost layers of soil, or it evaporates from the surface of the soil or vegetation. Most important for the replenishment of aquifers is the autumn precipitation (September-November) and snow cover melting during the spring months.

Effects of precipitation amounts and seasonal distribution can be summarized in following way:

- Temporal occurrence of the annual groundwater level maximum displays dependence on precipitation. A significant rise of groundwater level is observed during the autumn in years with the highest precipitation amounts. The autumn period of relatively rapid rise is followed by a local groundwater level decline, which obviously separates the period with aquifer replenishment from autumn rainfalls and the replenishment from snow cover melting (cf. the variations in the years 2001/2002 and 2002/2003 in Fig. 2).
- The most important for the time of occurrence of annual groundwater level maxima is obviously the precipitation in autumn and at the end of summer. This is apparent especially in the groundwater level changes in the NK 1 well in the year 2002, when the maximum was reached as late as in November as a consequence of extraordinary increased summer and autumn precipitation. The secondary maximum in spring 2003 reached a level, which was 20 cm lower than the autumn maximum.
- In the years with low precipitation amounts, the groundwater level maximum occurs only during the spring months as a consequence of snow cover melting. Autumn peaks are not observed (cf. the variation in the years 2000/2001 and 2003/2004 in Fig. 2).

5.2. AIR PRESSURE

It is very important to ascertain the response of groundwater level in the well to changes of air pressure, because air pressure fluctuations can produce groundwater level changes that could be mistaken for earthquake induced anomalies. Effects of air pressure on groundwater level fluctuation are most apparent in the HM 1 well (cf. Fig. 5). In order to determine the response of the groundwater level to air pressure fluctuations, we analyzed the relations between the daily mean groundwater levels and the daily mean air pressure values in the period from 23.10. to 25.11. 2002. The air pressure was measured at the meteorological station Cheb, which is operated by the Czech Hydrometeorological Institute (CHMI). Within the analyzed period a distinct correlation was detected between the air pressure and groundwater level. The groundwater level rise corresponds to the decline of air pressure, and vice versa. The correlation coefficient between the two data sets is $r_{xy} = -0.7157$. According to the test of the correlation coefficient, using Fisher's Z-transform, we consider the correlation to be proved at significance level $\alpha = 5\%$. The calculated correlation coefficient falls into the appropriate confidence interval (0.4869; 0.8527).

If we apply linear regression to the compared data sets, we obtain a regression line described by the equation $y = -0.0091\ x + 27.4750$ (Fig. 6), where x = air pressure in hPa and y = groundwater level in m. The standard error of the regression estimate is $s_{y.x} = 0.0673$, the mean residual value of regression $e = 0.0503$. None of the calculated residuals exceed the value $3^*\ s_{y.x}$, which would indicate the presence of extremely outlaying values. According to the above-mentioned equation a 91 mm change in groundwater level corresponds to the 10 hPa change of air pressure. Diurnal amplitudes of air pressure fluctuation exceeding 10 hPa are recorded relatively often at station Cheb.

The correlation characteristics listed above must, however, be considered to be valid only in the period for which they were calculated. The basic correlation characteristics between the air pressure and groundwater level are usually largely unstable in time, and the regression coefficients display substantial changes. It is probable that the groundwater level fluctuation is affected not only by local changes of the air pressure in the neighbourhood of the observed well, but also by regional air pressure fields. Therefore, it is quite difficult to eliminate air pressure effects on measured groundwater levels.

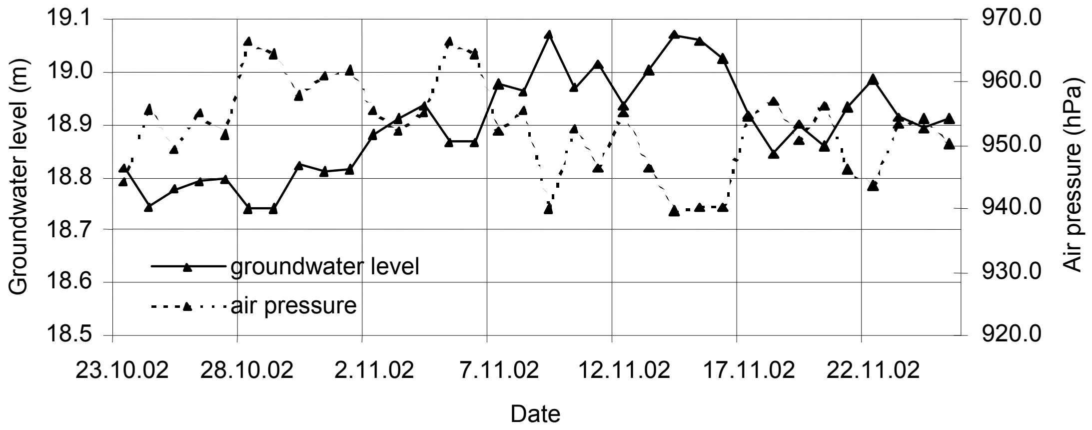

Fig. 5 Comparison of daily mean groundwater levels in the HM 1 well and daily means of air pressure measured at the meteorological station Cheb in the period 23.10. – 25.11. 2002.

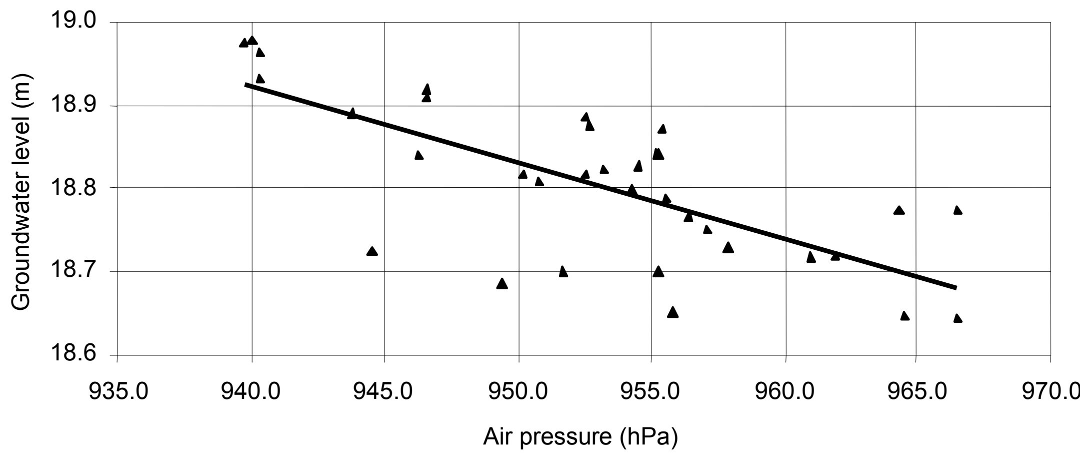

Fig. 6 Graph of linear regression between daily means of air pressure and daily means of groundwater level.

5.3. EARTH TIDES

The elastic deformations of the Earth produced by earth tides involve periodic volumetric expansions and compressions. They in turn produce oscillations in the water wells, mostly opposite in phase. At low tide, compression takes place, which causes a rise in the groundwater level, and vice versa. The response of the groundwater level to earth tides determines the sensitivity of the given aquifer to the volume crustal strain. Roeloffs (1988) assumed that the groundwater level responds to tidal strain in the same way that it responds to crustal strain of tectonic origin. Thus, the knowledge of tidal fluctuation amplitudes enables to determine the sensitivity of the observed aquifer to changes of the stress-strain conditions related to the preparation and rise of an earthquake.

Effects of earth tides are manifested in all the three observed wells with diurnal and semidiurnal cycles of groundwater level fluctuation. The most pronounced are these fluctuations in the NK 2 well (Fig. 7), where they reach the highest amplitude. The water level responds in the standard way, i.e. the decline is observed at high tide. The opposite type of response, i.e. groundwater level increase at high tide, is not observed. This case was described, e.g., by Vylita (1986) using data from the HJ 23 well in Karlovy Vary.

In order to determine sensitivity to volume crustal strain, tidal analysis of the measured groundwater levels was performed for particular observation wells. Measurements recorded every hour on the hour UTC (Universal Time Coordinated) was selected for the analysis. The computation was carried out for four main wave groups (O1, K1, M2, S2) according to Tamura's development with 1200 waves. The tidal model of an ellipsoidal, elastic, rotating

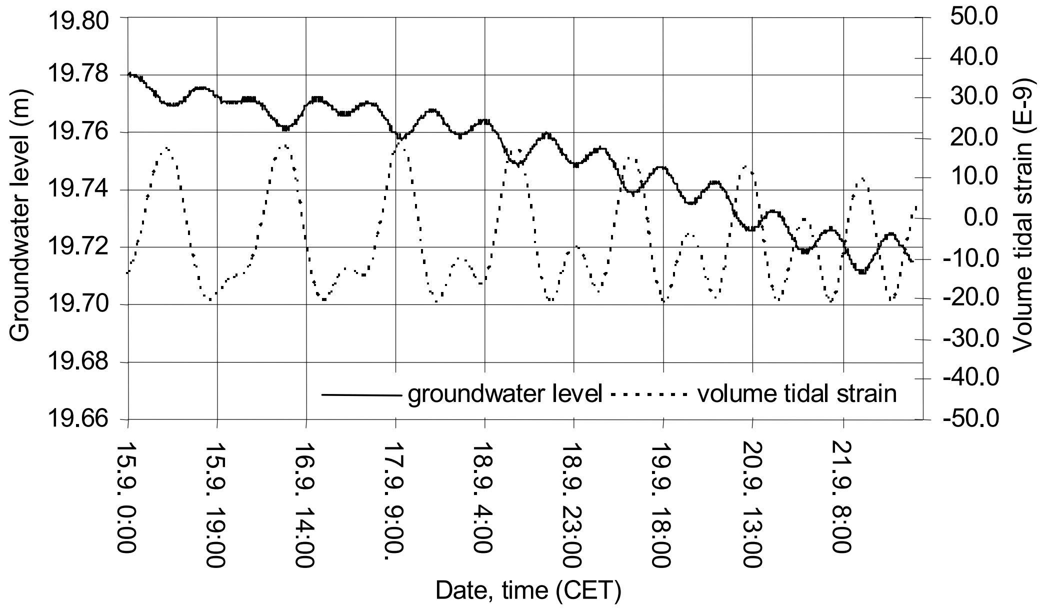

Fig. 7 Variations of groundwater level in the NK 2 well induced by effects of earth tides. Comparison of groundwater levels and relative volume tidal strain in the period 15.9. – 21.9. 2002.

Table 1 Results of tidal analysis of groundwater levels in the NK 1 well. Analysed period: 18.7. 2001 (13:00 UTC) – 23.6. 2003 (14:00 UTC). Number of hourly readings used for analysis: 14582. Number of filtered hourly readings used for analysis: 13532. Numerical filter used – Pertsev F2 of 50-hour length.

Group Nr.	Main wave	Period (h)	Amplitude Model (10^{-9})	Amplitude Observations (mm)	Amplitude factor (mm/10^{-9})	Time shift (h)
1	O1	25.819	6.807	0.394 ± 0.046	0.058 ± 0.007	-2.634 ± 0.482
2	K1	23.935	7.125	0.497 ± 0.046	0.070 ± 0.007	-3.848 ± 0.348
3	M2	12.421	7.027	0.266 ± 0.019	0.038 ± 0.003	-1.868 ± 0.141
4	S2	12.000	3.269	0.209 ± 0.019	0.064 ± 0.006	-1.945 ± 0.178

Table 2 Results of tidal analysis of groundwater levels in the NK 2 well. Analysed period: 2.10. 2001 (5:00 UTC) – 22.6. 2003 (8:00 UTC). Number of hourly readings used for analysis: 11060. Number of filtered hourly readings used for analysis: 9360. Numerical filter used – Pertsev F2 of 50 hour length.

Group Nr.	Main wave	Period (h)	Amplitude Model (10^{-9})	Amplitude Observations (mm)	Amplitude factor (mm/10^{-9})	Time shift (h)
1	O1	25.819	6.807	1.942 ± 0.082	0.285 ± 0.012	0.618 ± 0.172
2	K1	23.935	7.124	2.239 ± 0.082	0.314 ± 0.012	0.520 ± 0.139
3	M2	12.421	7.026	3.631 ± 0.077	0.517 ± 0.011	0.004 ± 0.042
4	S2	12.000	3.269	1.889 ± 0.077	0.578 ± 0.024	-0.345 ± 0.081

Table 3 Results of tidal analysis of groundwater levels in the HM 1 well. Analysed period: 18.7. 2001 (14:00 UTC) – 14.6. 2003 (16:00 UTC). Number of hourly readings used for analysis: 13134. Number of filtered hourly readings used for analysis: 11734. Numerical filter used – Pertsev F2 of 50-hour length.

Group Nr.	Main wave	Period (h)	Amplitude		Amplitude factor (mm/10^{-9})	Time shift (h)
			Model (10^{-9})	Observations (mm)		
1	O1	25.819	6.810	0.320 ± 0.155	0.047 ± 0.023	1.866 ± 1.993
2	K1	23.935	7.127	0.653 ± 0.155	0.092 ± 0.022	0.011 ± 0.910
3	M2	12.421	7.053	0.577 ± 0.061	0.082 ± 0.009	-0.454 ± 0.207
4	S2	12.000	3.281	1.083 ± 0.061	0.330 ± 0.018	-1.316 ± 0.114

Earth "Wahr-Dehant-Zschau" (Zschau and Wang, 1987), considering the imperfect elasticity of the Earth's mantle, was used for the analysed data. In addition to this model values of the relative volume tidal strain (derivation of this quantity cf. e.g., Melchior, 1983) were calculated, in order to determine the amplitude factors and phase differences between the theoretical and observed values. The amplitude factors represent the ratio of the observed values of groundwater levels in mm to theoretical values of the relative volume tidal strain in units of 10^{-9}. Since we are comparing quantities with different physical units, the amplitude factors do not verge on 1.0, which is usual in the case of standard tidal analyses.

The results of the tidal analyses are given in Tabs. 1 - 3. It is evident that the groundwater level in the NK 2 well reaches the highest amplitudes of tidal fluctuation. The maximum variations (3.631±0.077 mm) are induced by the M2 wave with a period of 12.42 hours. In the two remaining wells NK 1 and HM 1 the amplitudes of hourly readings of the groundwater level display practically negligible values, which for the most part do not exceed 1 mm. In order to compare the tidal fluctuations of groundwater level, the total range of adjusted values of observed tidal variations was determined for each well. The adjusted values of observed tidal variations represent the sum of all 1200 waves used, whose frequencies are given by the used tidal model, and the amplitudes A(O) and phases F(O) are calculated using formulas A(O) = A(M)*A(F), F(O) = F(M)+D(F), where A(M) and F(M) are the amplitudes and phases of the model values of volume tidal strain, A(F) is the amplitude factor and D(F) is the phase difference. The total range of observed tidal variations, determined in this way, reaches 18.99 mm in the NK 2 well, 5.3 mm in the HM 1 well and only 2.81 mm in the NK 1 well. This distinct difference in the sensitivity to tidal strain is given by different pressure conditions in the observed aquifers. While the NK 2 well is tapping a confined aquifer, aquifers observed through the NK 1 and HM 1 wells are unconfined. Generally it was proved that confined aquifers are more sensitive to crustal strain (cf., e.g., Kissin, 1982), since they are strongly limited in position to motion of water towards the overburden. The well tapping the roof of an aquifer is then considerably more important for the vertical motion of groundwater than in the case of unconfined aquifers. The changes of the water level induced by crustal strain are considerably more apparent in such a well.

Phase lags of tidal groundwater level fluctuations in comparison with the model values of volume tidal strain are relatively low. Time shifts exceed 2 hours only in case of O1 and K1 waves in the NK 1 well (cf. Tab. 1). Negative values of time shifts indicate a lag of the observed tidal fluctuations of groundwater levels behind the theoretical values of the relative volume tidal strain, whereas positive values indicate that the observed values precede the theoretical ones.

5.4. SEISMIC ACTIVITY

Several thousands of local earthquakes were recorded by local seismic stations during the whole period of monitoring. The major event was the August – December 2000 swarm, which consisted of 7017 micro-earthquakes in the magnitude range M_l = 0.0 – 3.3 (Fischer, 2003). Particular events of the whole swarm were distributed in time into nine distinct clusters P1 – P9 (cf. Fig. 8). The strongest events with magnitude $M_l \geq 3.0$ were recorded during the P2, P3, P5, P6 and P8 clusters. Notable changes in groundwater level fluctuation were observed only in the NK 2 well in connection with the P5 (October 15 – 17) and P8 (November 6 – 8) clusters. The anomalous behaviour of groundwater level differed slightly in both cases. Oscillations with amplitudes of several mm and lasting several minutes were recorded repeatedly in the case of the P5 cluster since October 13 (Fig. 9). These oscillations are a noticeably disturbing periodic tidal fluctuation, and after the cluster they completely disappeared. Since October 13 the groundwater level shows a downward trend, which stopped approximately 24 hours before the onset of the P5 cluster. After the cluster subsided, the downward trend appeared again, but it was steeper than the preceding trend. This type of fluctuations is not of "seismic origin" and it is caused by air pressure

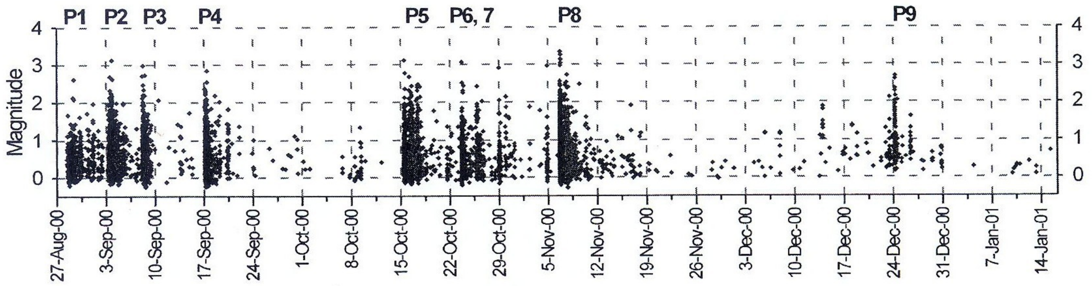

Fig. 8 Time distribution of seismic events of the August-December 2000 swarm (after Fischer 2003).

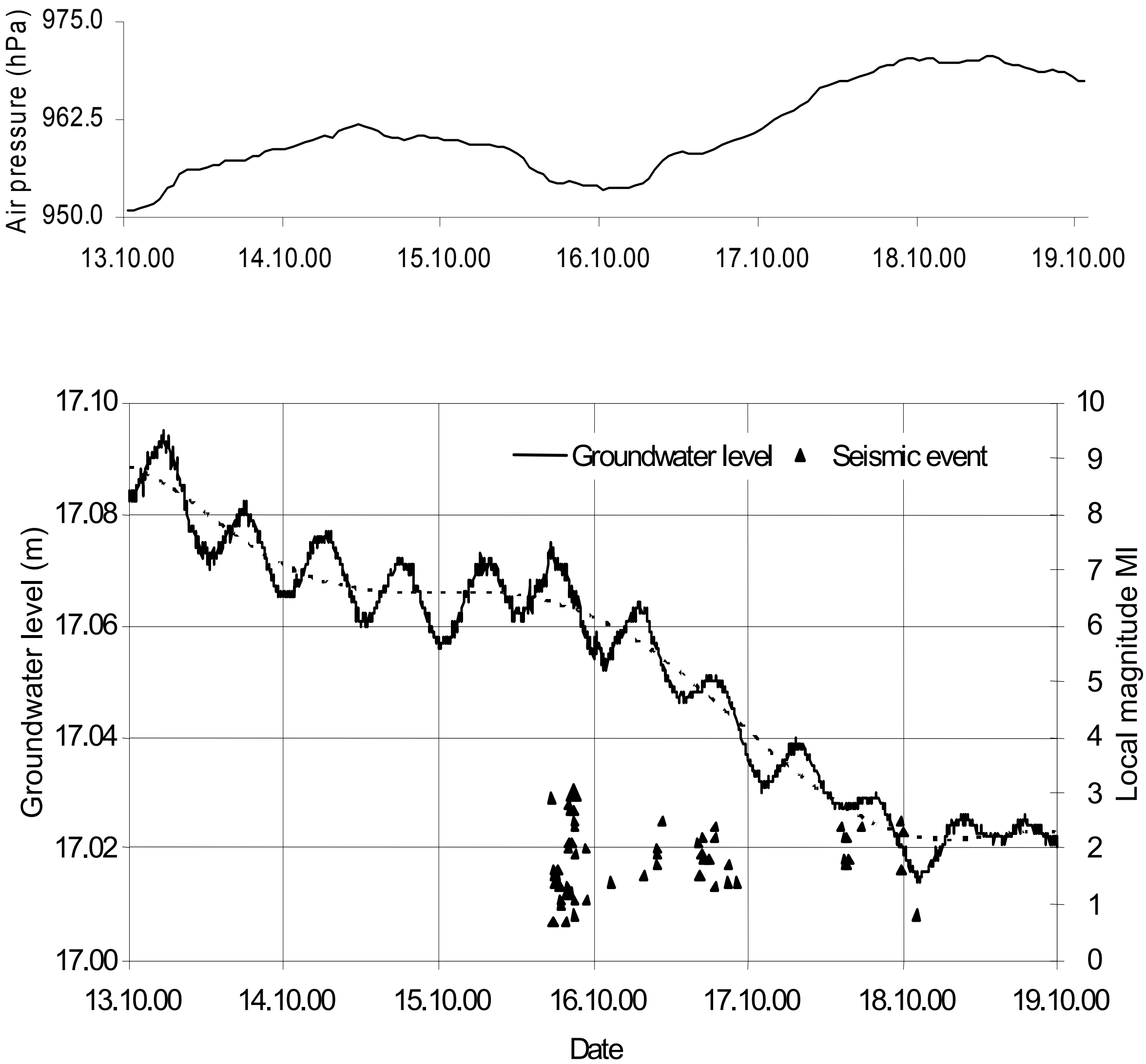

Fig. 9 Hourly observations of the air pressure and groundwater level anomalies recorded in the NK 2 well during the August-December 2000 swarm; cluster of events P5 between October 15 and 17.

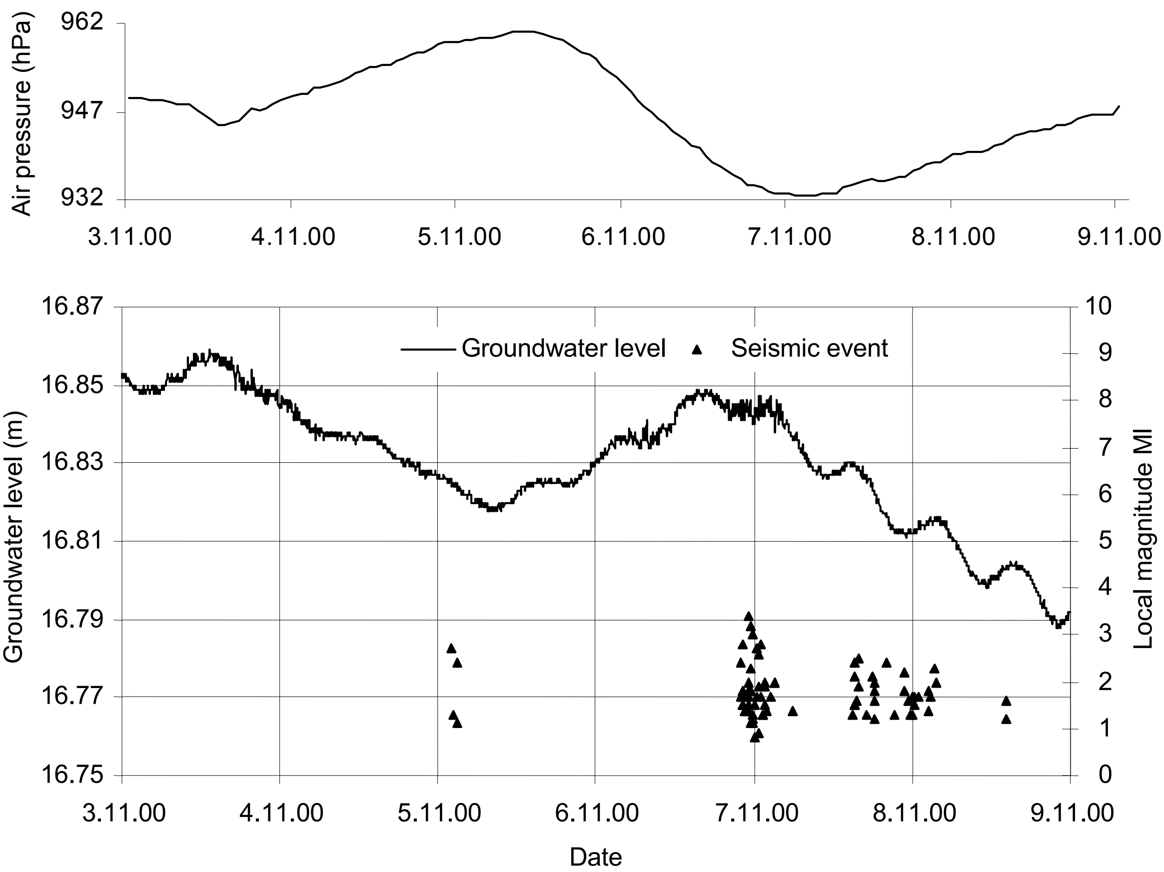

Fig. 10 Hourly observations of air pressure and groundwater level anomalies recorded in the NK 2 well during the August-December 2000 swarm; cluster of events P8 between November 6 and 8.

changes (cf. Fig. 9). Before the P8 cluster, the groundwater level fluctuation showed no anomalous behaviour for a relatively long time. The first anomaly was recorded only 16 hours before the first event of the cluster. Other, more significant oscillations were limited only to the time of duration of the cluster (Fig. 10). These oscillations had the same character as the oscillations before the P5 cluster, their maximum amplitude reached 9 mm. The cluster was followed by a relatively steep downward trend, which is however caused by the air pressure increase.

Groundwater level anomalies connected with the P1, P6, P7 and P9 clusters were not observed. Unfortunately the effects of the P2, P3 and P4 clusters recorded during September could not be evaluated. In the period from September 2 to 8 the measuring system was inoperative, and from September 17 to 18 the groundwater level in the NK 2 well was strongly affected by water pumping, which made additional interpretations impossible.

Abrupt variations in the range of 5.0 – 20.0 mm, which lasted only several minutes (Fig. 11) were simultaneously recorded in the period before the August – December 2000 swarm in the NK 2 and HM 1 wells between July 2 and 3. Connection of these anomalies with air pressure changes cannot be checked, because of missing air pressure values measured with appropriate frequency. The origin of these anomalies was interpreted once before as a phenomenon preceding earthquake activity (Brož, Bělař, 2002). From that point of view it is very important to note that the anomalous behaviour of several parameters such as the groundwater level, hydrostatic pressure, and free gas flow in wells and mineral springs of Bad Brambach in Germany (Koch et al., 2003) was also observed during July and August 2000.

To the basic statistic definition of above described anomalous fluctuations of groundwater level were used the time series of 3-minute groundwater level differences - GWD (i.e. differences of the two subsequently measured values). Occurrence of the anomalous fluctuation is consistent with the occurrence of GWD exceeding the value ±2sx, where sx is a standard deviation of the GWD data set in the selected period. As a case we present the course of

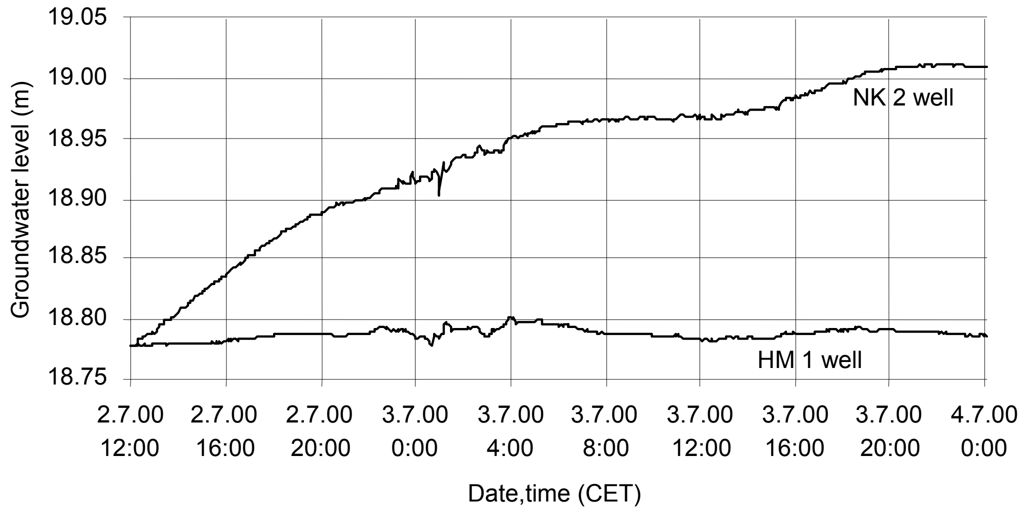

Fig. 11 Groundwater level anomalies recorded between July 2 and 3 in the NK 2 and HM 1 wells (after Brož and Bělař, 2002). In order to show both curves in one common graph the constant 2.15 m was added to the groundwater levels in the HM 1 well.

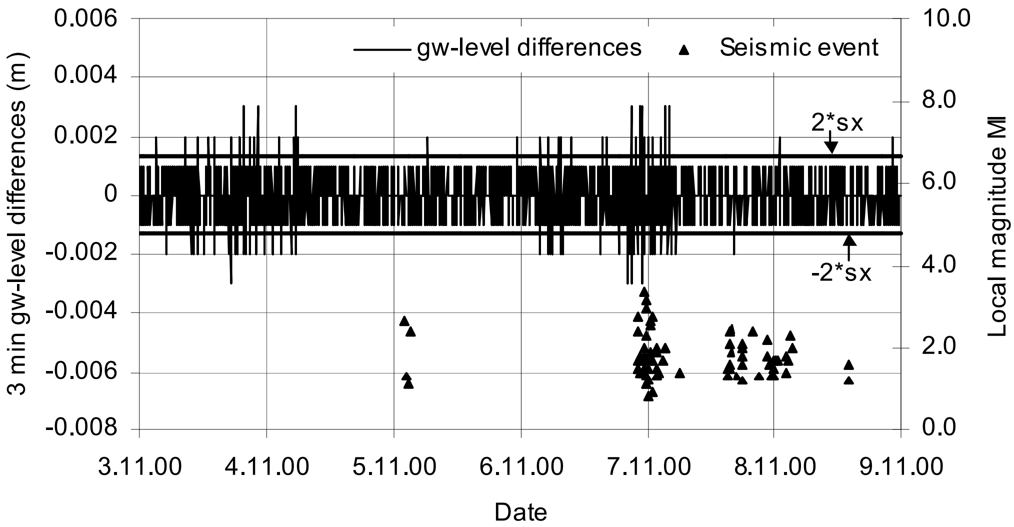

Fig. 12 3-minute groundwater level differences (GWD) in the period before and after the P8 cluster of the August – December 2000 swarm.

GWD in the NK 2 well in the period 3.11. – 8.11. 2000 (cf. Fig. 12). The time occurrence of anomalous GWD is summarized in tab 4 and 5 for anomalies recorded in July 2000 in HM 1 and NK 2 wells and anomalies in NK 2 well, related to P5 and P8 clusters of the August – December 2000 swarm. From these tables it is evident, that the GWD values exceeding ±2sx occurs in clearly definable clusters, whose delimitation defines the time interval of the anomalous behaviour of the groundwater level. Beyond these clusters occurs only minimum number of anomalous GWD (cf. Tabs. 4 and 5).

Further efforts focused on seeking groundwater level anomalies induced by earthquakes were not successful, although several local earthquakes with magnitude M > 2 were recorded. Larger earthquake swarms, similar to the August – December 2000 swarm, were not observed. For the present, we can assume that the reactions of fluids are restricted only to earthquake swarms, which, in contrast to particular seismic events, display larger amounts of released seismic energy.

Table 4 Occurrence of 3-minute groundwater level differences (GWD) exceeding ±2sx during the anomalous groundwater level fluctuations in HM 1 and NK 2 wells in July 2000.

Anomalous fluctuations			
HM 1, July 2000 (analysed period 2.7. 12:00 – 4.7. 00:00)		**NK 2, July 2000 (analysed period 2.7. 12:00 – 4.7. 00:00)**	
Period with GWD>2sx or <-2sx	Number of GWD >2sx or <-2sx	Period with GWD>2sx or <-2sx	Number of GWD >2sx or <-2sx
2.7. 23:57 – 3.7. 4:09	19	2.7. 23:21 – 3.7. 3:54	17
Non-clustered: 3.7. 10:57, 3.7. 15:30, 3.7. 23:24	3	Non-clustered: 3.7. 15:24	1
Sum of GWD>2sx or <-2sx	22	Sum of GWD>2sx or <-2sx	18

Table 5 Occurrence of 3-minute groundwater level differences (GWD) exceeding ±2sx during the anomalous groundwater level fluctuations related to P5 and P8 clusters of August – December 2000 swarm.

Anomalous fluctuations			
NK 2, P5 cluster (analysed period 13.10. 0:00-19.10. 0:00)		**NK 2, P8 cluster (analysed period 3.11. 0:00–9.11. 0:00)**	
Period with GWD>2sx or <-2sx	Number of GWD >2sx or <-2sx	Period with GWD>2sx or <-2sx	Number of GWD >2sx or <-2sx
13.10. 1:41 - 13.10. 18:44	31	3.11. 3:20 – 4.11. 5:59	40
14.10. 1:38 – 14.10. 4:02	4	6.11. 3:41 – 6.11. 9:32	13
15.10. 2:11 – 16.10. 4:02	47	6.11. 14:59 – 7.11. 5:20	31
Non-clustered: 14.10. 11:11, 16.10. 13:59, 18.10. 22:14	3	Non-clustered: 5.11. 6:29, 5.11. 23:20, 7.11. 16:35, 8.11. 1:05, 8.11. 22:29	5
Sum of GWD>2sx or <-2sx	85	Sum of GWD>2sx or <-2sx	89

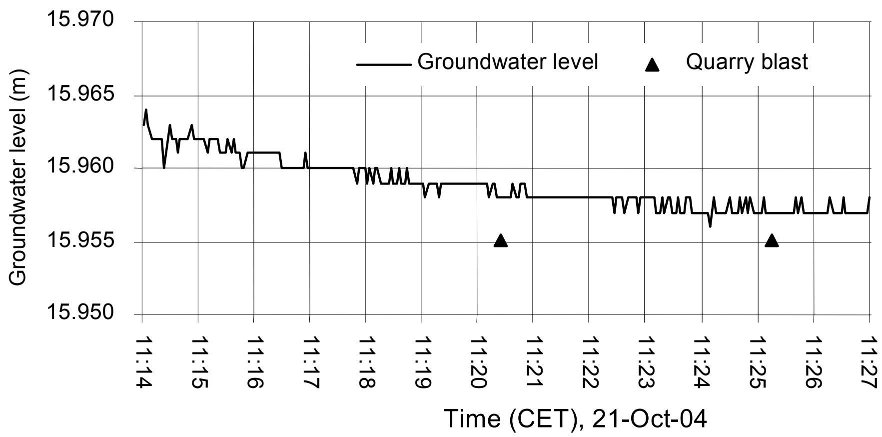

Fig. 13 Groundwater level fluctuation in the HM 1 well during two quarry blast measured with a sampling period of 1 sec.

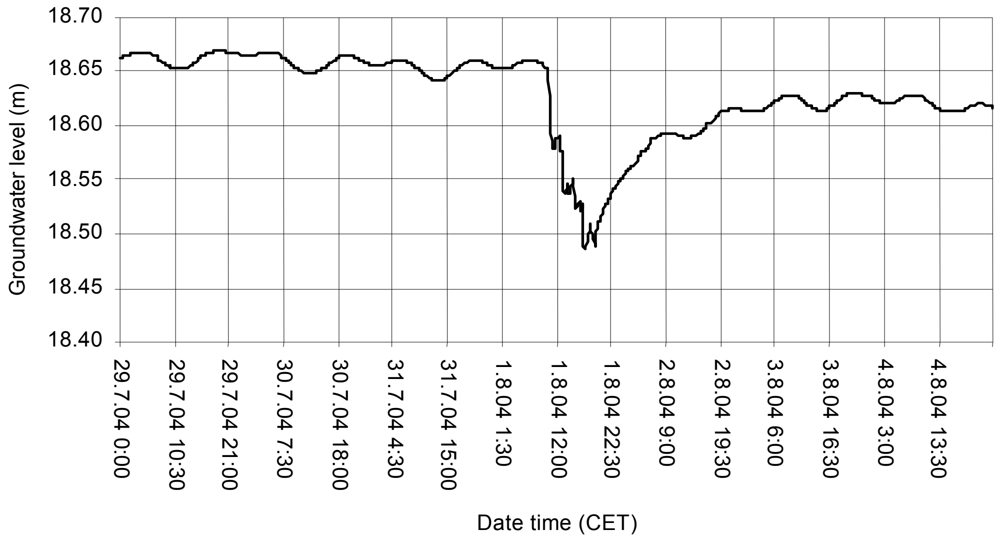

Fig. 14 Drop of groundwater level in the NK 2 well, caused by water drawing.

5.5. ANTHROPOGENIC EFFECTS

5.5.1. QUARRY BLASTS

Extraction works in quarries and mines often cause direct or indirect interventions in hydrogeological structures, which consequently result in changes of the groundwater regime. In our case it is necessary to keep in mind possible effects of blasts in the granite quarry near the municipality of Krásno. The Krásno-Vysoký Kámen deposit is a part of a granite body, which is about 600 m long and 400 m wide. An assessment of the possible effects of extraction works was carried out in the HM 1 well in the course of two blasts on 21. October 2004. For this purpose the sampling period of the groundwater level sensor was set to the lowest possible value, which is 1 sec. During the blasts set off at 11:20:45 CET (925 kg of explosive) and at 11:25:50 CET (1050 kg of explosive) no significant fluctuations were recorded in the HM 1 well (cf. Fig. 13). During the following days after the blast, no anomalous groundwater level behaviour was observed either.

5.5.2. GROUNDWATER WITHDRAWAL

Occasional groundwater withdrawal is reflected in the fluctuations of the water level in the NK 2 well. This observation well is situated approximately 10 m from a domestic well, used to supply water. Drawing groundwater causes sudden drops of the level of as much as several tens of centimetres (Fig. 14). Groundwater level fluctuations induced by drawing completely obscure the typical diurnal variations controlled by the effects of tidal forces. One can expect these fluctuations to obscure potential seismically induced anomalies, too.

6. CONCLUSIONS

Groundwater levels in the seismoactive region of Western Bohemia began to be monitored in June 2000, in order to observe potential relations between seismic activity and changes of the hydrogeological regime. By interpreting the data obtained in years 2000 – 2004, precipitation, air pressure and earth tides were determined as the main factors involved in the regime of observed aquifers. Significant anomalies related to seismic activity were recorded in the NK 2 well during the August – December 2000 earthquake swarm. The whole swarm was distributed in time into nine distinct clusters of seismic events. Noticeable changes of groundwater level fluctuation were recorded in connection with the October 15 – 17 and November 6 – 8 clusters. The anomalies had the character of repeated oscillations reaching several mm and lasting several minutes. These anomalies were observed in the groundwater level record before the first events of the clusters occurred and also during the clusters themselves. The two other observed wells, NK 1 and HM 1, displayed no similar response to the August – December 2000 swarm. These two wells, unlike the NK 2 well, tap unconfined aquifers and their sensitivity to crustal strain is thus considerably lower. This is also proved by the results of the tidal analysis of measured groundwater levels. The amplitudes of the main waves of the four analyzed wave groups are on average several times lower in the NK 1 and HM 1 wells than the amplitudes in the NK 2 well. It is, therefore, necessary to consider the pressure conditions in the aquifer in selecting wells for monitoring of earthquake-induced hydrogeological anomalies, in order to obtain plausible information about the effects of seismicity on fluids in the Earth's crust.

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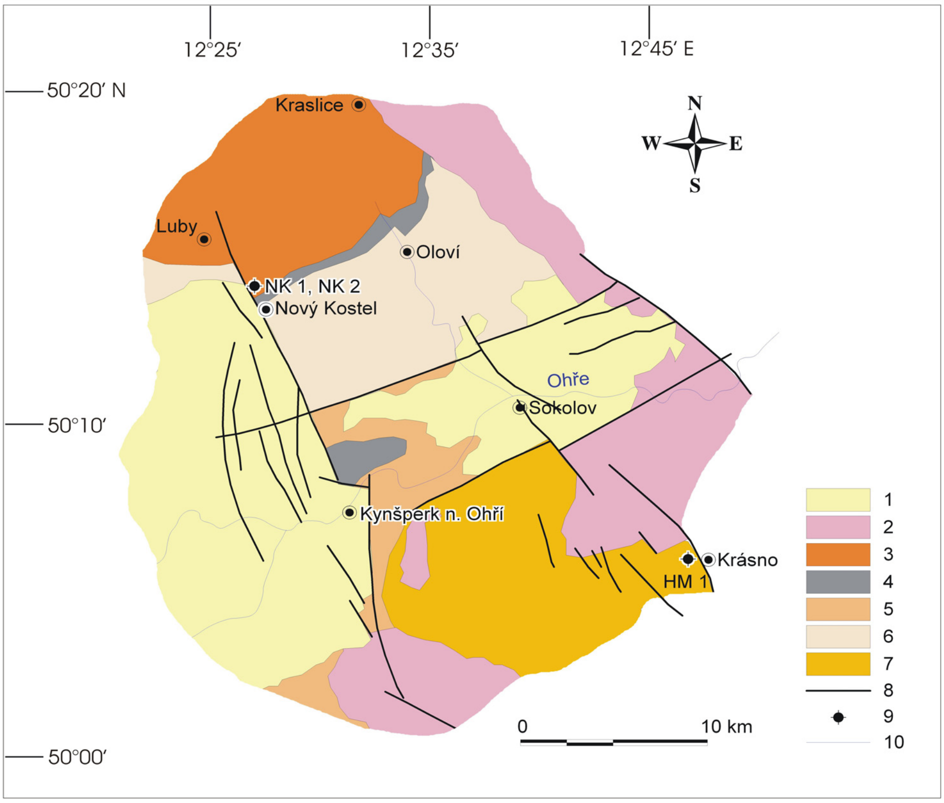

Fig. 1 Geological sketch map of the studied area with depiction of observed wells (after Mísař 1983). 1 – Neogene deposits, 2 – granites and granodiorites, 3 – phyllites, 4 – quartzites, 5 – mica schists and phyllites of the Kynšperk block, 6 – mica schists and phyllites of the Oloví block, 7 – Slavkov crystalline, 8 – tectonic fault, 9 – observing well, 10 – water course.

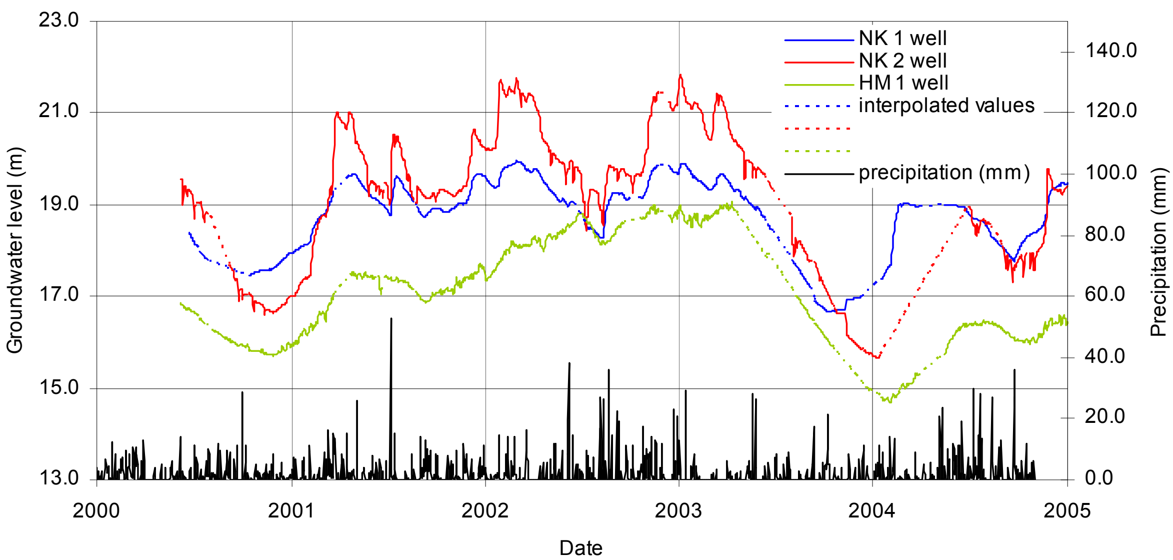

Fig. 2 Groundwater level fluctuations in the NK 1, NK 2 and HM 1 wells and precipitation aggregates measured at station Luby, 6 km NE of Nový Kostel.