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EVALUATION OF HORNA NITRA GEOTHERMAL RESERVOIR (CENTRAL PART OF SLOVAK REPUBLIC)

Miriam Fendekova[1] and Marian Fendek[2]
[1]Comenius University, Faculty of Natural Sciences, Department of Hydrogeology, Mlynska dolina, Pavilon G, 842 15 Bratislava, Slovak Republic
[2]Geological Survey of Slovak Republic, Mlynska dolina 1, 817 04 Bratislava, Slovak Republic

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ABSTRACT

Geothermal waters in the Horna Nitra Basin are bound to Triassic carbonates of the Choc and Krizna nappes, which are overlain by the basal Paleogene (breccias, conglomerates) above which are flyschoid facies and Neogene layers. Geothermal activity of the area is demonstrated on the surface by natural geothermal outflows at Chalmova (water temperature of 39 °C) and at Bojnice (45 °C). The mean value of heat flow density is 70 mW/m^2. Statistical methods and mathematical modelling by analytical and numerical models were used for analysis of regime and interrelationships of fresh groundwater and geothermal waters. Statistical analysis of data showed a seasonal character of groundwater level fluctuation in wells tapping geothermal waters at Bojnice. The influence of shallower cold groundwater was documented by groundwater level fluctuation in the well BR-4. A two-dimensional numerical model was used for evaluation of the geothermal resources of the reservoir. This model confirmed that the regime of level fluctuation in Bojnice is dependent mainly on geothermal water exploitation, and does not depend on precipitation directly. The model demonstrated that the exploitation rate from Bojnice should not exceed 27 l/s if the groundwater is to be stabilised at present levels. The total amount of geothermal energy of the Horna Nitra Basin was estimated to be 19.6 MW_t.

1. INTRODUCTION

The Horna Nitra Basin is located in the Central part of Slovak Republic (Fig. 1). It extends between the Ziar Mts. in the Northeast, Vtacnik Mts. in the Southeast and Strazovske vrchy Mts. in the West and Northwest. All the mountain ranges are separated from the Basin by faults.

The pre-Tertiary substratum is created by rocks of Ipoltica Group, predominantly Choc nappe carbonates in the central part, and Krizna nappe with envelope Mesozoic in the northern tract of the Prievidza depression. The basal Paleogene (breccias, conglomerates) and flyschoid facies overlie the Mesozoic substratum. The earliest Neogene – Eggenburgian is composed of conglomerates and sandy clays, overlain by calcareous, sandy clays interbedded with sandstones. The next sedimentation started in Badenian and was accompanied by volcanism. Thin coal beds overlie andesite tuffs near Janova Lehota. Younger filling of the basin consists of sedimentary and volcanic rocks (andesite conglomerates, sandstones, siltstones, coal beds, clays, tuffites). The youngest component of the Neogene filling of the basin is the Lelovce formation (fluvial gravels, sands, sandy clays and fresh water limestones).

Geothermal waters from Choc nappe carbonates are of Ca(Mg)-HCO_3 type with T.D.S. below 1 g/l, and those from the Krizna nappe fall into the Ca(Mg)-SO_4 type with T.D.S. of 1.3 g/l.

Data from two geothermal wells indicate that geothermal activity of the area is high. In the regional field the heat flow density values vary around 70 mW/m^2 and temperature at a depth of 1000 m ranges from 35 – 45 °C (Franko et al., 1995). Surface geothermal manifestations were known in Chalmova and Bojnice spas. The temperature of natural geothermal springs ranges from 39 °C to 45 °C.

Occurrence of natural healing sources of geothermal waters in Bojnice was the reason why the Bojnice spa was declared a natural therapeutic spa. Natural therapeutic spas are established by the Health Ministry of the Slovak Republic on the site of occurrence of natural healing sources or ambience favorable for healing, which are used for the purposes of spa treatment (Vandrova and Fendek, 1999). Only natural sources of declared healing can be used for the spa treatment (Slovak Parliamentary Act 277/1994, Coll., Art. 59, 60, Section 9).

Two deep geothermal wells were drilled in the basin. The first one was S1-NB drilled to the depth of 1688 m in Kos village in 1962. This well was cemented and a new one S1-NB II was drilled to a depth of 1851 m in 1980. Besides these wells, more than 15 wells with a depth from 30 to 1178 m were drilled close to the natural thermal spring outflows in the area of Bojnice spa. Some of them were used as geothermal water sources for spa operation and for swimming pools. Only 5 of them are operating at present. Potential utilisation of the well S1-NB II and its influence on the usable amount of geothermal waters in Bojnice spa was the aim of this study.

2. STATISTICAL ANALYSIS OF THE RELATIONSHIP AMONG FRESH AND GEOTHERMAL WATERS

Regime of fresh and geothermal waters was evaluated using data as follow:

- mean monthly groundwater levels in two geothermal wells NB-5 and BR-4 in Bojnice high block,
- mean monthly discharges of the Thermal Lake (representing natural outflows of geothermal waters) in Bojnice high block,
- total mean monthly discharge of all utilised geothermal sources in Bojnice spa,
- monthly yields of fresh groundwater springs in the adjacent area,
- monthly precipitation measured in the meteorological station in Prievidza (see general situation in Fig. 2).

All the data were obtained for the period 1990 – 1994.

At the same time a long–term hydrodynamic test was performed on the geothermal well S1-NB II consisting of:

- measurements of the static value of the hydrostatic pressure at the wellhead during the period 2.6.1993 – 7.7.1993,
- measurements of the temperature profile of the well and static value of the hydrostatic pressure at a depth of 1350 m in the period of 8.7. – 9.7.1993,
- measurements of the dynamic value of the hydrostatic pressure at a depth of 1350 m and at the wellhead, measurements of the free outflow, water temperature, air pressure and amounts of gasses in the period of 10.7. – 15.7.1993,
- measurements of the free outflow, water temperature and dynamic pressure value at the wellhead in the period of 16.7.1993 – 15.7.1994,
- pressure increase after the well S1-NB II was closed in the period of 15.7. – 12.8.1994.

During the hydrodynamic test on the well S1-NB II a free outflow of 26 l/s and temperature of 66 °C at the wellhead were measured.

Statistical evaluation of the input data was based on homogeneity assessment, analysis of the time series components and analysis of the interrelationships among geothermal and fresh water in connection to precipitation amounts. Homogeneity of time series was evaluated using normal probability plots and double mass curve method. Time series of Dubnica spring was used as a relative time series for double mass curve construction after its homogeneity was proved by proportional cumulative curve. Analysis of double mass curves for wells NB-5 and BR-4 was complemented by residual analysis (Fendekova and Fendek, 1993). Points, in which changes of the curve direction occurred, corresponded with the periods of minimum and maximum values of groundwater level due to seasonal fluctuation. No other influence was shown. Seasonal components of time series of precipitation, Dubnica spring yield and groundwater level in the well NB-5 are shown in Fig. 3.

The analysis of seasonal component showed that:

- in the well NB-5 minimal groundwater levels occurred in the period from November to March with the absolute minimum level regularly in February, maximum levels occurred in the period from May to July, with the absolute maximum level regularly in June,
- the situation estimated for the well BR-4 was quite similar, but the period of maximum groundwater levels was shifted to the period from April to July and the period of minimum groundwater levels to the period from December to March. The lower maximum groundwater levels in November indicates more intensive influence of shallow cold fresh water which reacted on precipitation maximum in November. The influence of shallow cold fresh water on geothermal water in the well BR-4 also indicated the shift of the maximum groundwater level period to the earlier spring months in accordance with the seasonal fluctuation of Dubnica spring fresh water.

The existence of decreasing trends in groundwater levels and yields of Dubnica spring was estimated. Cross correlation coefficients were used for analysis of interrelationships between pairs of time series. Statistically significant correlation coefficients were estimated for relationship of Dubnica spring yields and both wells NB-5 and BR-4 respectively. The highest value was 0.36 for the lag of +13 months (Fig. 4), but all correlation coefficients with lags of 11 – 15 months were statistically significant. The significance of the correlation coefficients was tested by Fisher's test of correlation coefficient significance, taking into account the length of a time series (Sachs, 1984). The same lag of 13 months was estimated for the relationship of precipitation and groundwater levels in wells NB-5 and BR-4, but the correlation coefficients were statistically insignificant (Fendek et al., 1997).

3. MATHEMATICAL MODELLING

An analytical model was created for free outflow of the well S1-NB II. Results of hydrodynamic measurements on S1-NB II performed in the period of 2.6.1993 – 12.8.1994 were used as the input data. The storativity coefficient was estimated using data from hydrodynamic measurements in 1980 when S1-NB was used as a piezometer. The estimated transmissivity coefficient was 4.52×10^{-3} m^2/s and the hydraulic conductivity had the value of 2.60×10^{-5} m/s. The storage coefficient had the value of 2.6×10^{-4} (Fendek et al., 1997). All estimated hydraulic parameters are in Table 1. The known value of storativity coefficient allowed the calculation of the skin effect. The best fit of the measured data provided the analytical model with the value of transmissivity coefficient of 4.52×10^{-3} m^2/s without any inflow. The model was used to calculate the maximal exploitation rate of S1-NB II of 20 l/s.

A distributed parameter numerical model for the Horna Nitra geothermal reservoir was created with the AQUA program package developed by Vatnaskil Consulting Engineers (1992) to solve the groundwater flow and mass transport by differential equations using the Galerkin finite element method with triangular elements. The model is two-dimensional.

The total surface area covered by the mesh was about 231.864 km^2. It covered the area of Bojnice high block up to outcrops of crystalline rocks of Strazovske vrchy Mts. in the northwest, Mesozoic rocks outcrops in Strazovske vrchy Mts. in the west and in Ziar Mts. in the east. As the south boundary, contact of impermeable young Palaeozoic rocks with carbonate aquifers was chosen. The pumping area was located in the western part of the modelling area. The model was created with 1966 nodes and 3685 elements. Boundaries were taken far enough away to avoid their influence on the solution. Boundary conditions for the distributed groundwater flow model were established based on geological setting, tectonics, geophysical measurements and water level measurements. The no-flow boundary was established along the whole reservoir area and only small areas in the surrounding mountains were used as boundary with constant potential. As for the initial state, prior to production it was assumed that the reservoir water head was constant.

The production rates were taken as monthly averages for each supply well from 1990 - 1994. The initial values for transmissivity and storage coefficient are taken from the results of well tests. A number of tests have been made in wells in the Horna Nitra geothermal reservoir in order to determine values of the aquifer transmissivity and storativity, and to locate impervious boundaries believed to exist between the two hydrothermal systems represented by Bojnice high block and separate deep structure of the rest of Horna Nitra reservoir. These two parts are divided by the Malomagursky fault. Tests were conducted by observations of water levels in observation wells after a supply well was turned off or on. Hydraulic parameters were calculated from the recovery test curves using the Theis equation modified by Jacob transformation. Linear model of regression analysis was used for division of the graph of drawdown vs. log (time). Individual parts of the semilogarithmic graph were fitted by straight lines using the least squares method. The correct fitting was also controlled by the difference between the measured and the fitted value of the hydrostatic pressure. The representative part for hydraulic parameters estimation was selected by the total logarithmic conversion difference. Its utilisation is always helpful when results of some hydrodynamic well tests of the same cased parts of the well or aquifer are available. Results of the regression analysis model were used for time t_0 determination which is used for storativity calculation (Fendek, 1997).

The transmissivity, storage coefficient, anisotropy and porosity were determined by matching observed and calculated reservoir response. The **transmissivity** in the area covered by the model varied from **4.2×10^{-3} to 6.3×10^{-6} m^2/s.** The lowest value for transmissivity was obtained for the well NB-8 and in the area to the southwest (see Figure 2) and the highest value were obtained in the area of wells S1-NB II, BR-1, BR-2 and NB-7, as well as for carbonate aquifers of Krizna and Choc nappes outcropping to the surface in Strazovske vrchy Mts. and their spreading in the pre-Tertiary substratum in the eastern part of the area.

The **storativity coefficient** in the area covered by model ranged from **5.1×10^{-4} to 5.1×10^{-6}**. The highest values were used in the area of wells BR-1, BR-2 and NB-7, as well as for carbonate aquifers of Choc nappe outcropping to the surface in Ziar Mts. and for carbonates in the pre-Tertiary substratum in the northeastern and northwestern part of the area.

The model was used to predict geothermal water level in four cases:

1. Total exploitation rate of 50.6 l/s, consisting of 30.6 l/s exploited in Bojnice high block and 20.0 l/s from the well S1-NB II, representing the deep part of Horna Nitra geothermal reservoir,
2. Total exploitation rate of 61.5 l/s, consisting of 41.5 l/s exploited in Bojnice high block and 20.0 l/s from the well S1-NB II,
3. Total exploitation rate of 36.3 l/s, consisting of 16.3 l/s exploited in Bojnice high block and 20.0 l/s from the well S1-NB II,
4. Total exploitation rate of 72.6 l/s, consisting of 30.6 l/s exploited in Bojnice high block, 15.0 l/s from the well S1-NB II, representing the deep part of the Horna Nitra geothermal reservoir and from two fictive wells placed to the east from the Malomagursky fault.

The results obtained showed that in the case 3 an increase of geothermal water levels occurred in the whole area of the Bojnice high block in the range of 1.05 – 3.55 m. The increase was higher in the northern part of the Bojnice high block (wells NB-5, Pa-7, BR-4, BR-5 and BR-6) and lower in the southern part or the area (wells NB-7, NB-8 and BR-2). No change of the geothermal water level in the well S1-NB II was caused. In case 2 a decrease of geothermal water levels between 0.68 and 2.43 m occurred in the whole area of the Bojnice high block. The exploitation rate did not cause any change of groundwater level in the well S1-NB II. These results suggest that there is a particular exploitation rate, which will result in stable geothermal water levels in the Bojnice high block. From the modelled cases it follows that the total exploitation rate in Bojnice high block should not exceed 27 l/s. For the deep part of Horna Nitra geothermal reservoir 42 l/s was estimated to be the optimum exploitation rate. The total amount of thermal-energy potential of geothermal waters in Horna Nitra basin was estimated to the value of 19.6 MW$_t$.

4. CONCLUSION

The regime of geothermal waters of the Horna Nitra geothermal reservoir including Bojnice high block and their relationship to groundwater of surrounding mountains was evaluated. The main problem to be solved was to prove or disprove the interconnection between the Bojnice high block and the deep part of the Horna Nitra geothermal reservoir. Potential utilisation of geothermal water from the well S1-NB II and its influence on the usable amount of geothermal waters in Bojnice spa had to be investigated.

Statistical analysis of data showed the seasonal character of groundwater level fluctuation in wells tapping the geothermal waters of Bojnice high block. The existence of decreasing trends in groundwater levels and yields of Dubnica spring was estimated. The influence of shallower cold groundwater was documented by groundwater level fluctuation in the borehole BR-4. No influence of long-term (1-year) hydrodynamic test performed on the borehole S1-NB II was documented in the case of Bojnice high block geothermal waters.

An analytical model was used to estimate the maximal exploitation rate of the well S1-NB II on 20 l/s by free outflow. A two-dimensional numerical model confirmed that the regime of level fluctuation in Bojnice high block is dependent mainly on geothermal water exploitation, and it does not depend on precipitation directly. This conclusion is in agreement with the results of a statistical analysis, which shows no relationship between precipitation and geothermal water levels.

The numerical model demonstrated that the exploitation rate from the Bojnice high block should not exceed 27 l/s if the level of geothermal water is to be stabilised at present levels. It was confirmed that the Bojnice high block structure and deep geothermal reservoir of Horna Nitra are two independent structures separated by the Malomagursky fault. The utilisation of geothermal water from the well S1-NB II will not influence the exploitation rate in the Bojnice spa.

The total amount of thermal-energy potential of geothermal waters in Horna Nitra Basin was estimated to the value of 19.6 MW$_t$.

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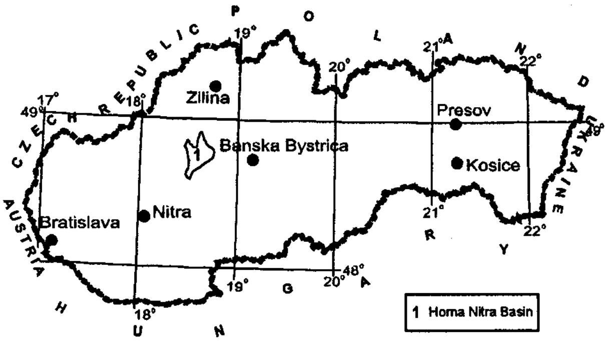

Figure 1. Location of the Horna Nitra Basin

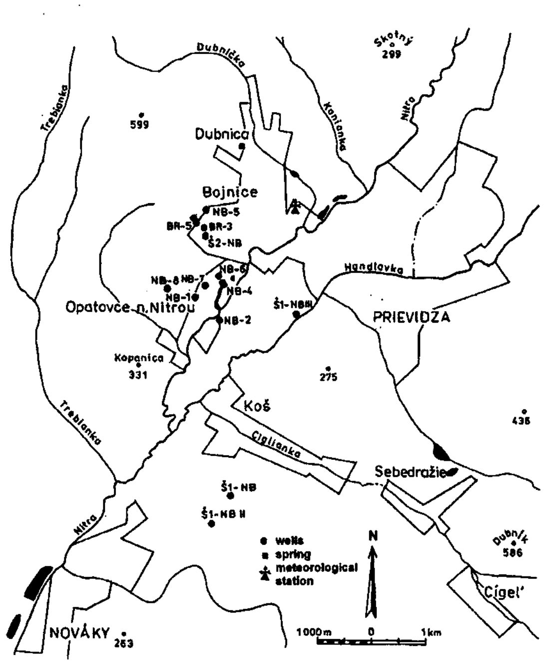

Figure 2. General situation

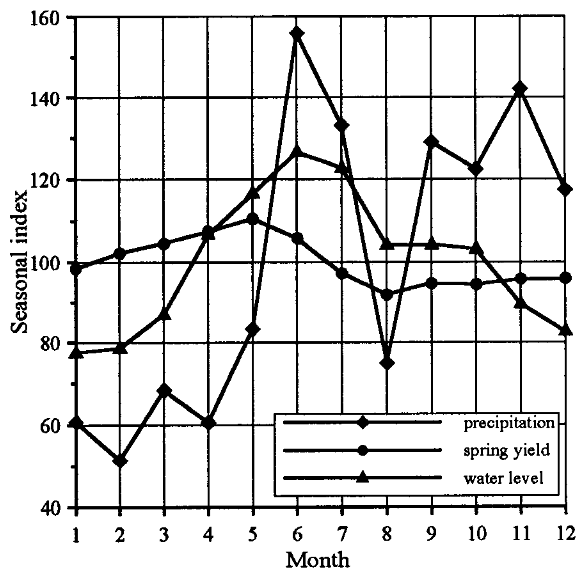

Figure 3. Seasonal Components of Time Series of Precipitation (Prievidza), Spring Yield (Dubnica) and Geothermal Water Level (Well NB-5)

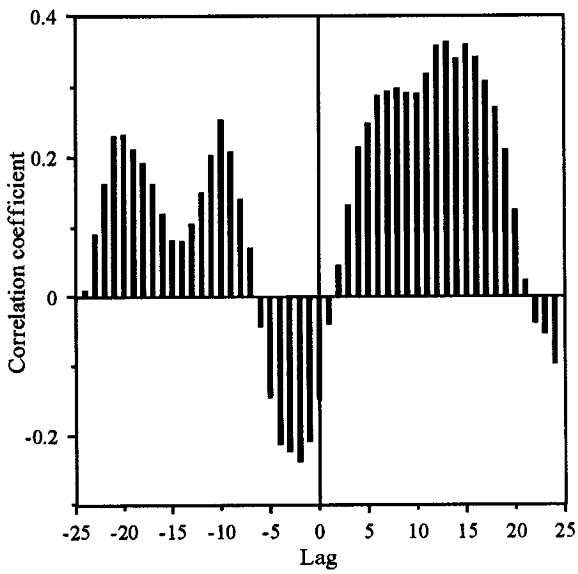

Figure 4. Cross-correlation of Geothermal Water Level (Well NB-5) and Spring Yield (Dubnica)

Table 1. Results of hydraulic parameters calculation for S1-NB II geothermal well

Date	Coefficient of intrinsic transmissivity (m^3)	Coefficient of transmissivity (m^2/s)	Coefficient of hydraulic conductivity (m/s)	Coefficient of storativity
16.06.1980	1.15×10^{-10}	2.61×10^{-3}	1.50×10^{-5}	
16.06.1980	1.26×10^{-10}	2.86×10^{-3}	1.65×10^{-5}	1.0×10^{-4}
02.07.1980	6.86×10^{-11}	1.56×10^{-3}	8.95×10^{-6}	
02.07.1980	1.57×10^{-10}	3.56×10^{-3}	2.05×10^{-5}	2.6×10^{-4}
15.07.1994 I	1.23×10^{-10}	2.78×10^{-3}	1.59×10^{-5}	
15.07.1994 II	2.01×10^{-10}	4.52×10^{-3}	2.60×10^{-5}	