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TECHNICAL ARTICLE

The Relationship Between Groundwater in the Nováky Coal Deposit and the Thermal Waters from the Bojnice High Block (Slovakia)

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Abstract
Slovakia is very poor in coal reserves but it is extremely rich in mineral and thermal water resources. The Nováky coal deposit is situated near the Bojnice spa, which is among the oldest and most important spas in Slovakia. Due to their proximity, there is a risk that coal mining could adversely affect the Bojnice thermal water resources. We evaluated the results from several surveys as well as groundwater monitoring (inflows to the mining area, overflows from surface wells, and groundwater levels relative to the aquifer systems) and groundwater chemical processes near the Nováky coal deposit and explained the relationship between the groundwater in the Nováky coal deposit and tectonically uplifted Bojnice High Block.

Keywords Monitoring of groundwater · Coal mining · Groundwater chemical processes · Drainage of coal deposit · Mine water

Introduction

The Nováky coal deposit is located in the Upper Nitra basin, which is bordered on the eastern side by the neogene volcanic Vtáčnik mountain range, on the northeastern side by the crystalline basin in the Žiar mountain range, and on the northwest side by the Little Magura mountain range, in which the vertically raised Bojnice High Block, containing the Bojnice spa, is located. The Little Magura mountain range consists of Mesozoic crystalline and limestone-dolomitic rocks and is a part of the Strážov highlands, which borders the Upper Nitra basin on its western side.

The relative proximity of the Bojnice thermal springs and Nováky coal deposit (Fig. 1) is of concern since protection of the Bojnice thermal springs has always been a priority. The relationship between the Nováky coal deposit and Bojnice thermal water resources began to be investigated in January 1954, when there was an inrush of "thermal" water of ≈ 10 L s^{-1} at a temperature of 25 °C at the main section of the 1st horizon (+80.00 m above sea level (a.s.l.) of the Mládež mine. Half a year after the inrush, the yield of the Bojnice thermal springs decreased from 39 to 15 L s^{-1}.

Research on the groundwater resources from the Nováky coal deposit and the Bojnice thermal water actually started in 1961, though coal mining took place from 1939 to 1941 and to a greater extent (since) from 1951. However, there was no continuous or permanent monitoring of groundwater for hydrogeological purposes. Individual inflows were rarely measured and the total inflow to the mine was determined by the running time of the pumps and the nameplate rating. Only in 1964 was a groundwater monitoring system introduced to clarify the hydrogeological conditions of the Nováky coal mines (Mier, Lehota, and Mládež mines; Fig. 1) and the relationship between the groundwater of the mines and Bojnice thermal water resources.

An Overview of the Site's Hydrogeological Characteristics

With respect to the mining operations, the following aquifer systems were identified at the Nováky coal deposit: an overlying aquifer system, an underlying aquifer system, and the Triassic aquifer system.

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The overlying aquifer system is represented by the aquifer clasts of the Quaternary, which in the northwestern part of the deposit gradually joins with the detrital-volcanic formation cluster (Lehota and Lelovec Formations). The Quaternary is represented by alluvial and diluvial sediments from the Nitra river and its tributaries. The alluvial sediment is represented by flood clays and silts with a thickness from 0.5 to 3.0 m, and is predominantly composed of a silt, clay, and sand admixture. Within the subsoil, there is sandy gravel with a thickness of 15–25 m. This admixture contains more sand and less silt and clay. The gravel has a hydraulic conductivity coefficient from 2.50×10^{-4} to $3 \times 12 \times 10^{-6}$ m s^{-1} (Kováč et al. 1978). The diluvial sediments of the Quaternary are represented by silty and stony debris and weak rounded stone.

In the northwest part of the Nováky coal deposit (Nováky formation), the overlying aquifer system is represented by the detrital-volcanic Lehota and Lelovec Formations, which formed in limnic-fluvial conditions. The Lelovec formation comprises a much thicker, black, clayey-sandy sedimented layer with some gravel(s), decaying conglomerates, sandstones, non-saline limestones, and clay lenses from 100 to 200 m thick.

The Lehota formation (Fig. 2) is considered a synvulcanic sedimentary formation, which appears to be a relic of a paleocanal of NW-SW river flow, which passed through the Vtáčnik mountain range towards the Žiar basin (Šimon et al. 1997a,b). The formation is comprised of irregularly alternating, poorly-sorted gravel and sand, sandy clay, and clay with Mesozoic carbonate rocks and quartzites, considered as graded under Paleozoic granitoids and Paleogene sandstones. This formation is characterized by an increased clay fraction. This has created several local closed aquifers, which are separated by impervious clay horizons. The coefficient of hydraulic conductivity reaches the value of $k = 4.13 \times 10^{-5}$ to 9.85×10^{-9} m s^{-1} (Kováč et al. 1978). These local aquifers create "pressure subhorizons," mostly in a negative piezometric level.

This robust unit (the overlying aquifer system) is the most important aquifer in the studied area; intergranular permeability prevails over fracture permeability. In the Nováky depression, it creates an extensive hydrologically uniform groundwater reservoir with a free groundwater surface, which is in direct hydraulic connection with the water level in the Nitra river and its tributaries. Due to the impermeable positions in this unit, there are also pressurized subhorizons, accompanied mostly with a negative groundwater level. The infiltration of the whole area is large, because it is fed by both rainwater and surface water from the watercourses of the Nitra and Handlovka rivers. Although the system is rated as a free surface system, local subhorizontal layers with a positive piezometric level were also verified by drilling. For example, at borehole Z 394 T (Fig. 3), which was drilled and equipped in the Lehota and Lelovec formations (Fig. 2), the piezometric level at the borehole collar reached a pressure of 9.2 kPa after the level had stabilized (Vondráček et al. 1989) and 10.1 kPa in May 2018. This clearly demonstrates that drainage of the overlying aquifer system did not affect the groundwater level for this section of the Nováky coal deposit.

The underlying aquifer system is formed by the Kamenec formation (Fig. 2), which exists just below the entire coal deposit. It consists of secluded clasts and the supposed "underlying tuffites", which together represent a complex of fluvial to fluviolimnically redeposited rocks of varied granulometric composition. The Kamenec formation is ≈ 350 m thick in the southern part of the Nováky coal deposit. The underlying aquifer system is isolated from the overlying aquifer system by almost the entire area of the Nováky coal deposit, the Koš formation (in the mine-operational concept, "overlying clays"), and the Nováky formation, which contains the coal seam, which together create a confining layer. An exception is the eastern and northeastern edge of the deposit, as well as the Nováky depression itself, where, due to strong reductions or absences of the Koš formation, the underlying and overlying aquifer systems are interconnected.

The tuffs of the underlying aquifer form an artesian horizon of pressurized water with a negative, but sometimes positive, piezometric level, which has developed only into a descending wing. The infiltration area of this aquifer is situated on the eastern edge of the deposit, i.e. in places where the Kamenec formation rises to the surface and is replenished by precipitation. Replenishment of water reserves is also taking place in the eastern and northeastern part of the deposit, in places where various clays of the Koš formation are wedged. The Kamenec formation at the eastern edge of the Prievidza basin protrudes as an exposed 1–3 km wide strip. To the west, it copies the storage conditions of the Paleogene underlier, but due to the influence of the tectonics, falls to about 700 m, where it wedges (Fig. 3). The underlying aquifer system is fractured and porous. The whole complexity of the underlying aquifer system consists of a series of sub-horizontal, alternating permeable and impermeable rocks, which are hydrologically connected to each other (Šarkan et al. 2009).

Based on the hydrophysical parameters, the underlying aquifer system can be divided into two sections. In the upper part (100–130 m below the main coal seam), the permeability coefficient (k) varies from 2.66×10^{-6} to 9.14×10^{-6} m s^{-1}. In the lower part of the formation, there is more tuffite-clay (at the expense of tuffites and conglomerates) and the coefficient k ranges from 5.67×10^{-6} to 8.91×10^{-9} m s^{-1} (Halmo et al. 2001a).

Based on an initial 1940 exploratory well Z 14 (Fig. 3), the original piezometric level in the underlying aquifer system was ≈ + 305.4 m a.s.l. (Table 1), which reflects the

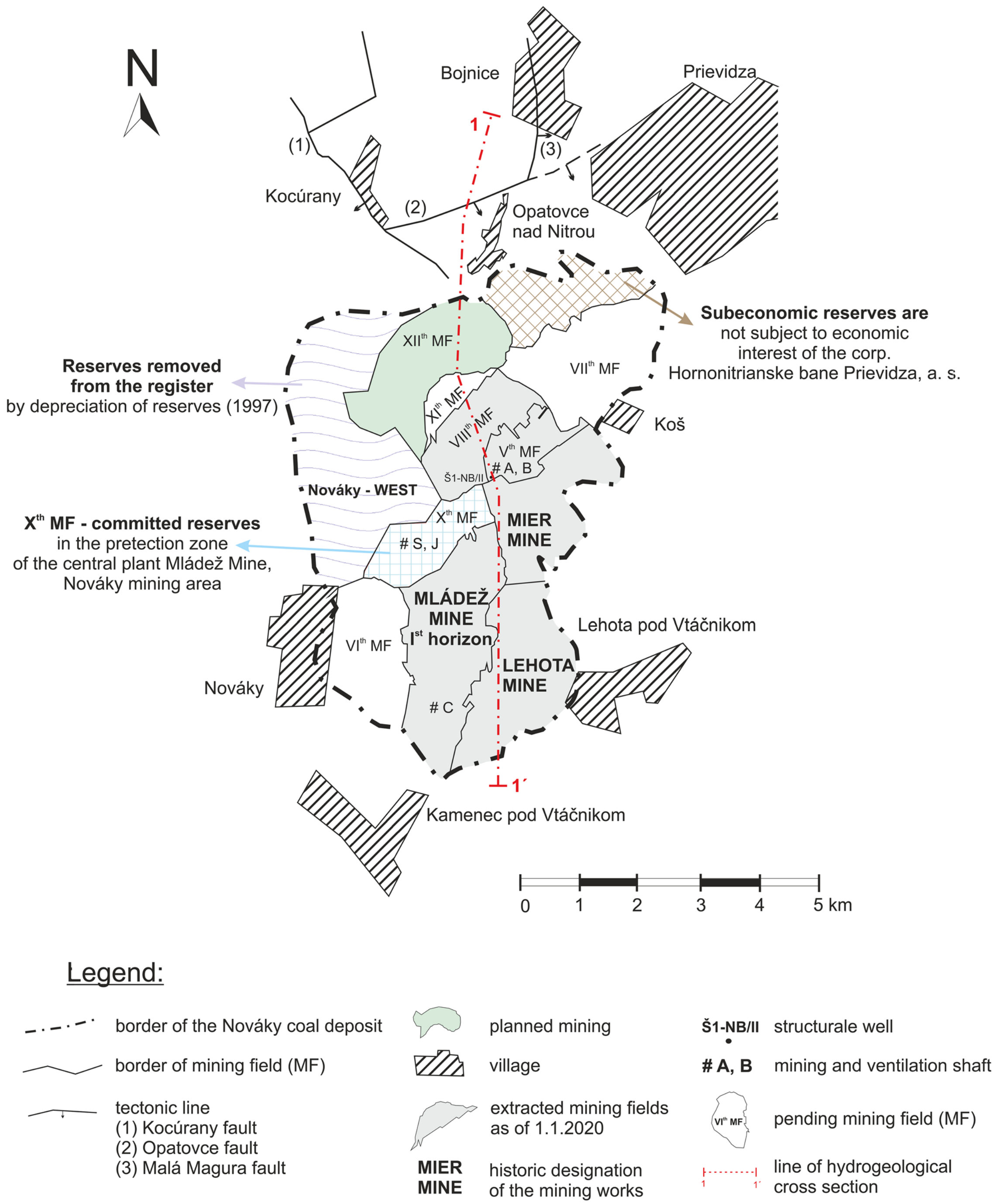

Fig. 1 Geological position of the Nováky coal deposit and Bojnice spa (Halmo et al. 2019a)

altitude of the terrain where the Kamenec formation outcrops below the Quaternary layer. The underlying aquifer system was drained based on the excavated site to a level of ≈ − 45 m a.s.l, which gradually reduced the groundwater level to this level (Fig. 4). The deepest auxiliary pumping station was at − 220 m a.s.l., which reduced the groundwater level in the Kamenec formation by as much as 525 m.

At present, for operational reasons, this pumping station is closed, and the groundwater level is maintained at about 90 m a.s.l. This started the gradual revitalization of the underlying aquifer system. The hydroisopies shown in Fig. 4b show the levels of the Nováky coal deposit that intersect with the piezometric levels of the groundwater in the underlying Kamenec formation aquifer system.

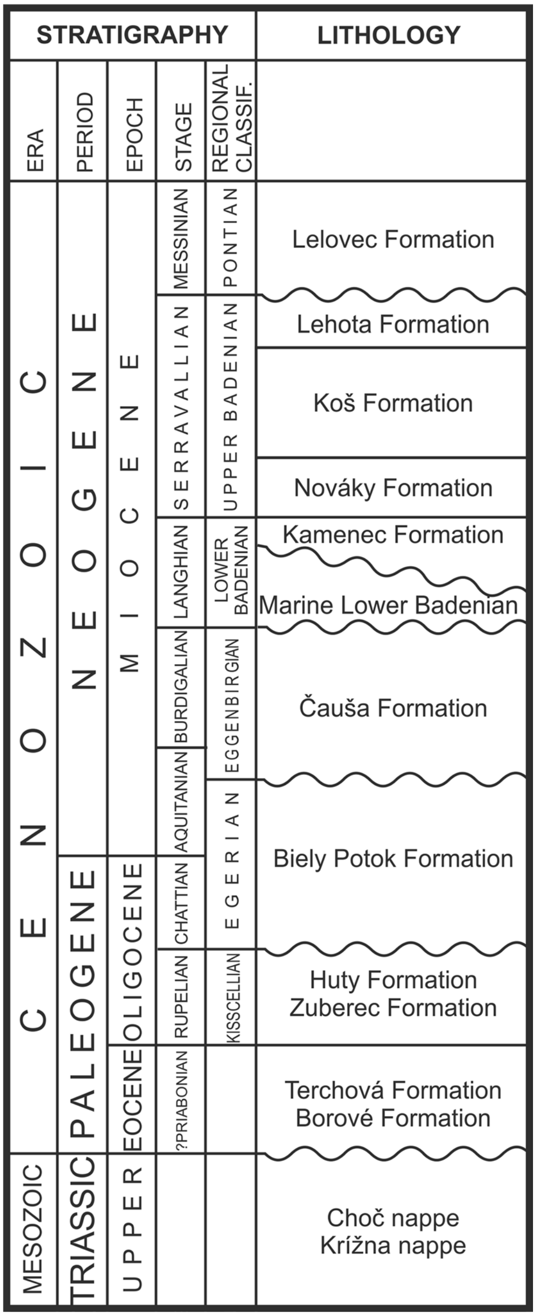

Fig. 2 Lithostratigraphy of the Upper Nitra basin sediments (Šimon et al. 1997b)

Carbon-14 dating of the water in wells NC-13H (6699 ± 210 years) and Z-408P (34,891 ± 3872 years) indicates that the groundwater tuff was not part of the hydrogeological cycle (except for water at the eastern edge) and stagnated (Vondráček et al. 1990). As mine drainage began, the natural conditions were disturbed by the pumping; the water of the underlying aquifer system began to circulate, causing the natural circulation on the eastern edge of the deposit to accelerate. The direction of groundwater flow is currently controlled by the location and geometry of the drainage structures (Borovicová 2020).

In the past, the underlying dewatering system was a much-discussed and considered model of deep depression, which was associated with the risk of "suction" thermal water from the deep subsoil of the basin through an approximately 600–800 m thick complex of predominantly pelitic Paleogene rocks. For this reason, surveys and mode measurements on wells were carried out at Z-370P and Z-371H (Fig. 3). During the long-term pumping tests on the well Z-371H (1st interval Baden, 2nd interval Egenburg) the discharge level from the nearby wells Z-320H and Z-370P (Fig. 3) was not affected, which confirmed the open position of the Schliers clays (Čausa formation) can be evaluated as an insulator (Vondráček et al. 1986).

The Triassic aquifer system is formed by the basal Paleogene and Triassic rocks of the Choč nappe (Fig. 2). These layers are hydrologically integrated into one uniformed unit. In the Upper Nitra basin, in the overburden of the Triassic aquifer system, there are several 100 m thick complexes of Paleogene impermeable clay rocks, which form the confining layer of the underlying aquifer system.

The basal Paleogene Borové formation was deposited in a transgressive time period. It consists of dewatered basal clastics of the Paleogene and mainly consists of carbonate breccias, carbonate conglomerates, carbonate sandstones, and organogenic limestones. The cement of the breccias and conglomerates is a carbonate-sandy material. The greatest thickness of the Borové formation was verified at well Š1 NB (Fig. 3) to be 138.4 m. This formation's permeability coefficient ranges from 1.51×10^{-5} to 3.40×10^{-6} m s^{-1}, as measured at boreholes NB-1 and NB-6 (Fig. 3; Halmo et al. 2001a). Mesozoic rocks are petrographically represented by the dewatering of partially crushed sediments from the limestone-dolomitic complex mixture of the Choč mantle (middle Triassic) with a permeability coefficient of 8.95×10^{-6} to 2.05×10^{-5} m s^{-1} (Vondráček et al. 1989). Collected rock samples have a fracture permeability, especially in the Bojnice High Block, and karst permeability, which was verified, as examples at the test borehole site BR-1 (Fig. 3). The piezometric groundwater level ranges from 54.62 m above the terrain (NB-1) to 2.75 m below the terrain.

The Triassic aquifer system in the Upper Nitra basin is the subsoil of the Nováky coal deposit and is located at a depth of ≈ -1600 to -1800 m a.s.l. (1000–1200 m below the coal seam). The hydraulic parameters were determined based on the results of a long-term well waterflow test at the well Š1-NB-II (Fig. 3), which lasted from June 1993 to August 1994: transmissivity $T = 2.25 \times 10^{-3}$ m^2 s^{-1}; storativity $S = 4.4 \times 10^{-4}$; diffusivity $D = 5.10$ m^2 s^{-1} (Halmo et al. 2001a). Within the area of the Bojnice spa, the Triassic aquifer system is located at a depth of 72 m (verified by the test

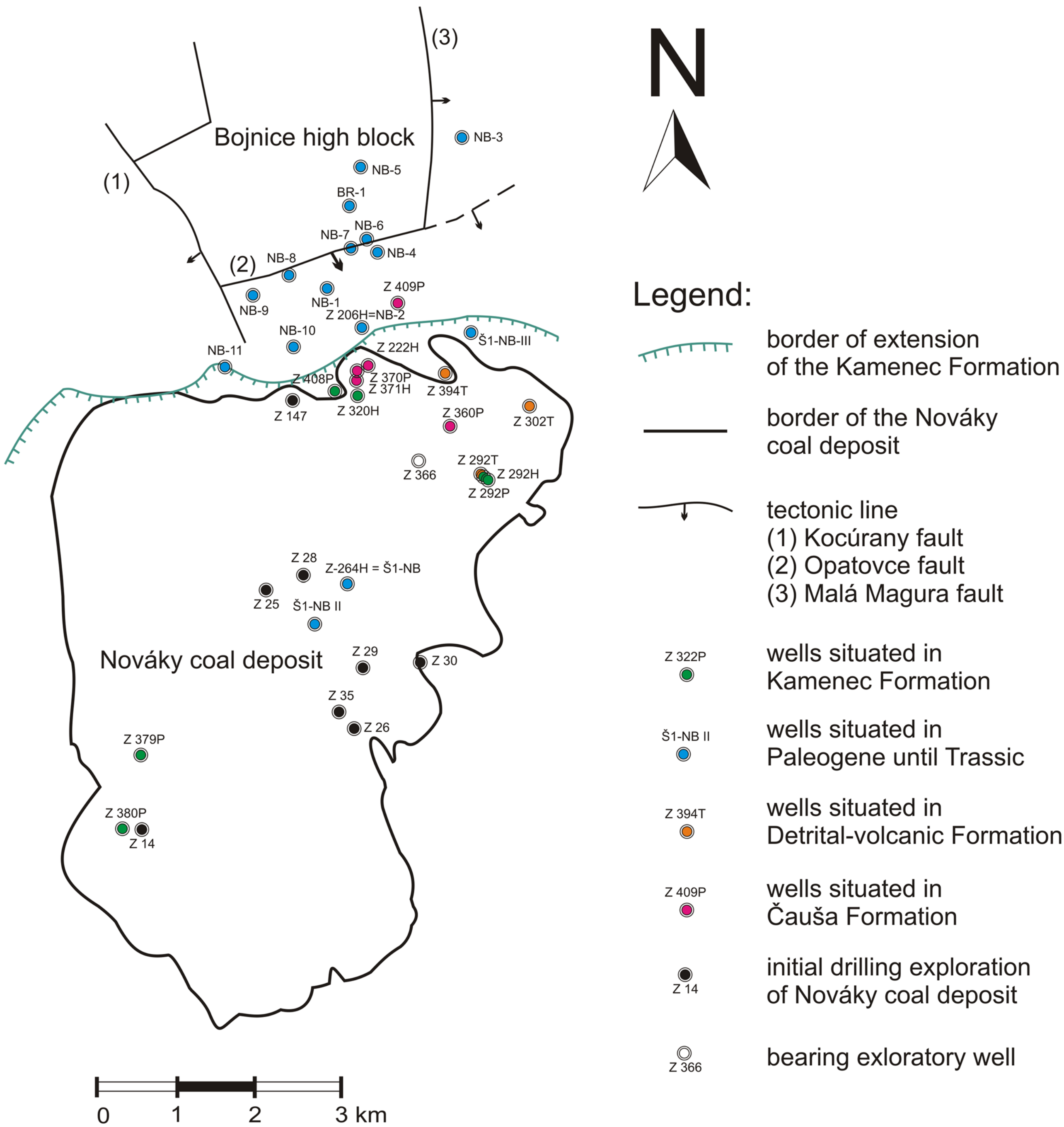

Fig. 3 Schematic map of the assumed extension of the Kamenec formation on the northern side of the Nováky coal deposit (Borovicová 2020)

Table 1 The oldest hydrogeological data from underlying aquifer system (Halmo et al. 2019a,b)

Borehole marking	Z 14	Z 25	Z 26	Z 28	Z 29	Z 30	Z 35	Z 147
Year of imprementation	1940	1941	1941	1941	1941	1941	1941	1954
Overflow dimension (m a.s.l.)	255.4	255.7	303.7	255.9	287.9	290.5	291.8	260.7
Inflow dimension (m a.s.l.)	− 73.23	− 8.2	262.4	− 6.9	109.17	234.4	108.4	172.6
Overflow rate (L s^{-1})	5.0	2.0	11.0	25.0	10.0	15.0	2.66	10.0
Water temperature (°C)	28.0	–	–	20.0	–	–	–	–
Steady pressure (MPa)	0.50	–	–	–	–	–	–	–

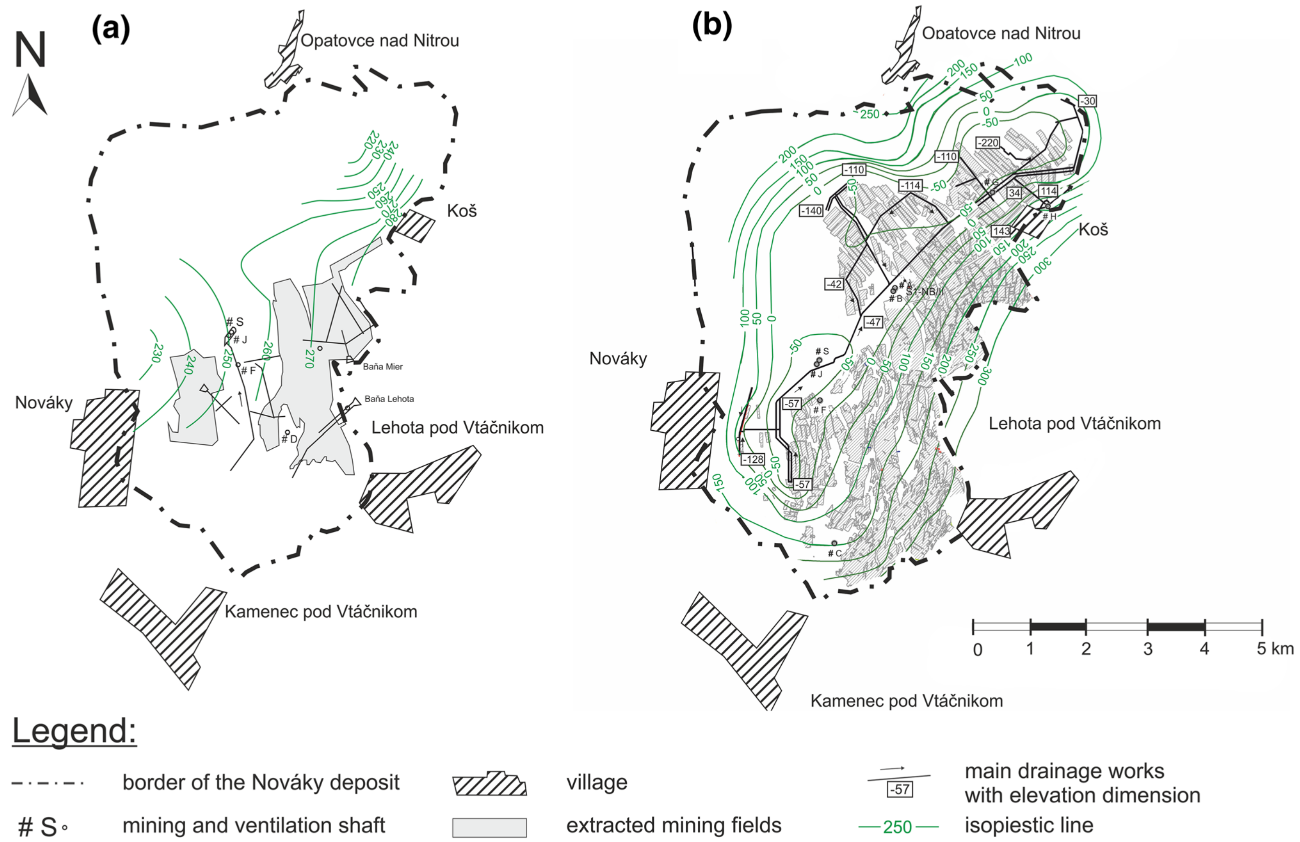

Fig. 4 Formation and extent of a depressive cone in the underlying aquifer system over time: **a** years 1956–1959 (Malatinský et al. 1963); **b** year 2018 (Halmo et al. 2019a)

site well NB-5—Fig. 3) up to 935.5 m below the surface (verified by NB-1 well—Fig. 3).

The Choč Nappe rocks were most significantly affected by the hydrochemical composition created by the Triassic aquifer system and the water of this system exists in the Nováky depression and also in the Bojnice High Block, with a positive piezometric level.

The thermal water of the Bojnice High Block in the Paleogene and Mesozoic rocks show a relatively small range of carbon-14 dating values, from ≈ 8600 to 12,700 years. It is evident that they belong to one spring structure with both intensive circulation and mixing, while the water from the boreholes of the Upper Nitra basin, which extend into the Paleogene and Mesozoic, have a much older carbon-14 dating of 18,000 to 45,000 years (the limit of carbon-14 dating). J. Šilar (in Makuša and Šuchová 1986) assumed that the water of the Bojnice High Block probably comes from the beginning of the Holocene to the latest Pleistocene. In contrast, the thermal water of the Upper Nitra basin has a very low carbon-14 content and a very long residence time and can be considered to be fossil water that originated in the Pleistocene and has not yet become part of the hydrological cycle. No test specimen from the Bojnice High Block or the Upper Nitra basin contained a measurable concentration of tritium, which would indicate recent contact with the atmosphere (Šilar 1985, in Makuša and Šuchová 1986).

Drainage of the Coal Deposit Since 1940

The beginning of drilling in the Nováky coal deposit dates back to 1939, but almost no hydrogeological observations were made at the exploration wells until 1956. The only exceptions are the boreholes where artesian water emerged at the surface during drilling (Table 1). It was not until 1956 that reconnaissance pumping tests using sludge were carried out at some of the wells in an effort to obtain hydrogeological data near the coal deposit, while other pumping was focused on the underlying aquifer system.

The beginning of a systematic mining hydrogeological survey and subsequent drainage of the overburden and subsoil of the Nováky coal deposit started only after the catastrophic inrush of mine water on 15 August 1963 during removal of the Lehota overburden (Fig. 1). After the catastrophic inrush of mine water in 1963 at coalface no.

3204 and the Lehota mine, the commission of inquiry recommended retaining at least 30 m of the overlying clays of the Koš formation, though it was considered necessary to remove some of these layers when drilling into aquifers at an overburden height of 30 m.

The "safe layer" of overlying clays with a minimum thickness of 30 m was probably determined on the basis of the relationship between the heights of the destructive landslide. Before then, a 6 m layer thickness was considered to be the maximum possible thickness of layer that could be mined simultaneously. The general bulking coefficient was sand as 1.2. This means that if we insert this data into the equation (Eq. 1), we get exactly five times the economic coal thickness (i.e. 30 m) for the height of the overburden (Kromková and Seko 2020; Kubica and Kroul 2013).

$$h_z = \frac{m}{k_0 - 1} = \frac{m}{1,2 - 1} = 5m \tag{1}$$

where: h_z = height of the fold overburden (m); m = thickness of coal seam (m); and k_0 = bulking coefficient.

The prevention of mine water inrushes became a corporate research task addressed by the Mining Research Institute of Prievidza in technical cooperation with the Nováky Coal Mines. Their aim was to find the most suitable method of drainage (Fides et al. 1966). In addition to the thinning and absence of overlying clays in the peripheral parts of the deposit (the Lehota mine and southeastern part of the Mládež mine), the nature of the tributaries from the overlying aquifer system was also affected by uneven development of the overlying Koš formation clays.

At the beginning of the 1980s, it was decided that the best way to solve the drainage problem was by building mining galleries (Supplemental Fig. S-1). In principle, these excavations were used to excavate a coal seam or in the upper third of the Kamenec formation (the underlying aquifer system), which in cooperation with mining boreholes create an efficient gravity-drainage system without the need for pumping technology. These drainage corridors were excavated in advance of mining and were used in the pre-drainage for the 2nd stage of the Mládež mine project and northeastern edge of the Nováky mine (Halmo and Šnirc 1984; Halmo et al. 1994).

As the deposit was excavated and mined, boreholes oriented to drain the abandoned excavation areas were installed. These so-called “waste wells” reduced the worst water levels of the excavated areas during the opening, preparation, and mining in the adjacent parts of the coal deposit. One of the most serious and complex problems that had to be addressed in this manner was the drainage of the acquired areas of the former Mier mine, which was followed by the former mining location of the V mining field (MF, Fig. 1). Drainage was carried out by a combination of surface and underground wells, but over time, surface wells proved to be unsuitable ($Q_{underground\ wells}$ = 33.3 L s^{-1}, $Q_{surface\ wells}$ = 3.0 L s^{-1}) and economically unviable for this purpose (Halmo and Šnirc 1984).

Gradual verification of the storage conditions of the Nováky coal deposit, as well as the process of exploitation, followed extraction of the coal reserves in the Mier and Lehota mines (Fig. 1). At the level of the 1st horizon, the construction opening of the mining works, especially in the deeper parts of the deposit at the 2nd level horizon only vertical introductory mining works were built. In addition, the basic opening works were also excavated in the underlying Kamenec formation. By excavating the main trenches with a system of boreholes (security and drainage), a drainage screen was created in the underlying aquifer system at an elevation of ≈ − 45.0 m a.s.l. This produced an extensive pressurized depression basin (Fig. 4). Long-term groundwater measurements at observation wells built into the underlying aquifer system were used to monitor the development of the drainage process over time and space and showed that the decline in groundwater levels had a linear character (Fig. S-1) (Fig. 5).

From Fig. S-1, it is clear that due to the squeezing process of mining, boreholes Z 303H, Z 337P, and Z 357P, which were originally built as observation boreholes into the Kamenec formation, were cut off in the area of the detrital-volcanic formation. Subsequently, they became only observation wells, reflecting the groundwater level in the overlying aquifer system (Lelovec and Lehota formations).

From 1954 to December 2019, more than 272.4 million m^3 of mine water was extracted from Nováky coal deposit, equivalent to more than 68% of the volume of the Lac des Dix in Switzerland. Up to 41% of the total amount of depleted mine water has come from the underlying aquifer system. This created a large groundwater depression, especially in the Kamenec formation (Fig. 4). The formation and the increase of this depression has been monitored by regular water level measurements at surface and underground wells (Fig. S-1).

Influence of Coal Mining on the Underlying Aquifer System

The radiocarbon age determination indicates that the groundwater in the tuffs were not part of the hydrogeological cycle in the past (except for water on the eastern edge) and had stagnated (Vondráček et al. 1990). With the beginning of drainage, the natural conditions were disturbed. As a result, the water of the underlying aquifer system began to circulate and circulation at the eastern edge of the coal deposit accelerated. At present, the direction of the flow of the underlying mine water is controlled by the position and geometry of the drainage voids and pumps.

The underlying aquifer system in the southwestern part of the deposit, in the area of the mining field VI (Fig. 1) with its tensioned binary aquifer, was significantly affected by mining. As the hydrostatic pressure dropped below the saturation pressure (P = 1.04 Mpa) during the dewatering of the deposit, the water segregated into a water and gas (methane and mixtures of methane and nitrogen). The methane content ranges from 50.57 to 96.99% (Halmo and Pokojný 1987). Both phases were then filtered through the same medium, with the total permeability for the phase mixture always being less than for each phase separately. Due to constant drainage from the underlying strata and associated reduction of the hydrostatic pressure, the water permeability of the drainage system decreased as the gas evolved from the rock in this area, which caused the dewatering process to slow down. Meanwhile, the gas permeability increased since the viscosity of gas is much less than water and since gas can effectively migrate from elsewhere, given the new pressure conditions. After the opening of the coal seam and the expansion and enlargement of the filtration area, there was a substantial increase in the exhalation of methane into the mining areas. The initial hydrostatic pressure at the bed layer ranged from 3.3 to 4.7 MPa (Halmo and Pokojný 1987). It currently ranges from 0.0 to 2.5 MPa.

Genesis of Thermal Water in the Upper Nitra Basin and the Bojnice High Block

The origins of the thermal water of the Upper Nitra basin and the Bojnice High Block are determined by the geological structure; all the main parts of the artesian-type hydrogeological structure (infiltration, transit-accumulation, and springs) are important. The composition of the limestone-dolomitic complex plays an important role in the chemistry of the thermal water, which is enriched during the transition of its individual components and acquires its total mineralization of 0.7–0.9 g L^{-1} and Palmer-Gazda classification (Gazda et al. 1971) of Ca-Mg-HCO_3(+ SO_4). This chemical composition indicates that the groundwater filters through a system of cracks and fissures in the limestone-dolomitic complex to a depth of 2500–3000 m, especially in the Upper Nitra basin. The Earth's natural heat flow (≈ 80 mW m^{-2}) and a thermal gradient gradually heats the water to ≈ 70 °C,

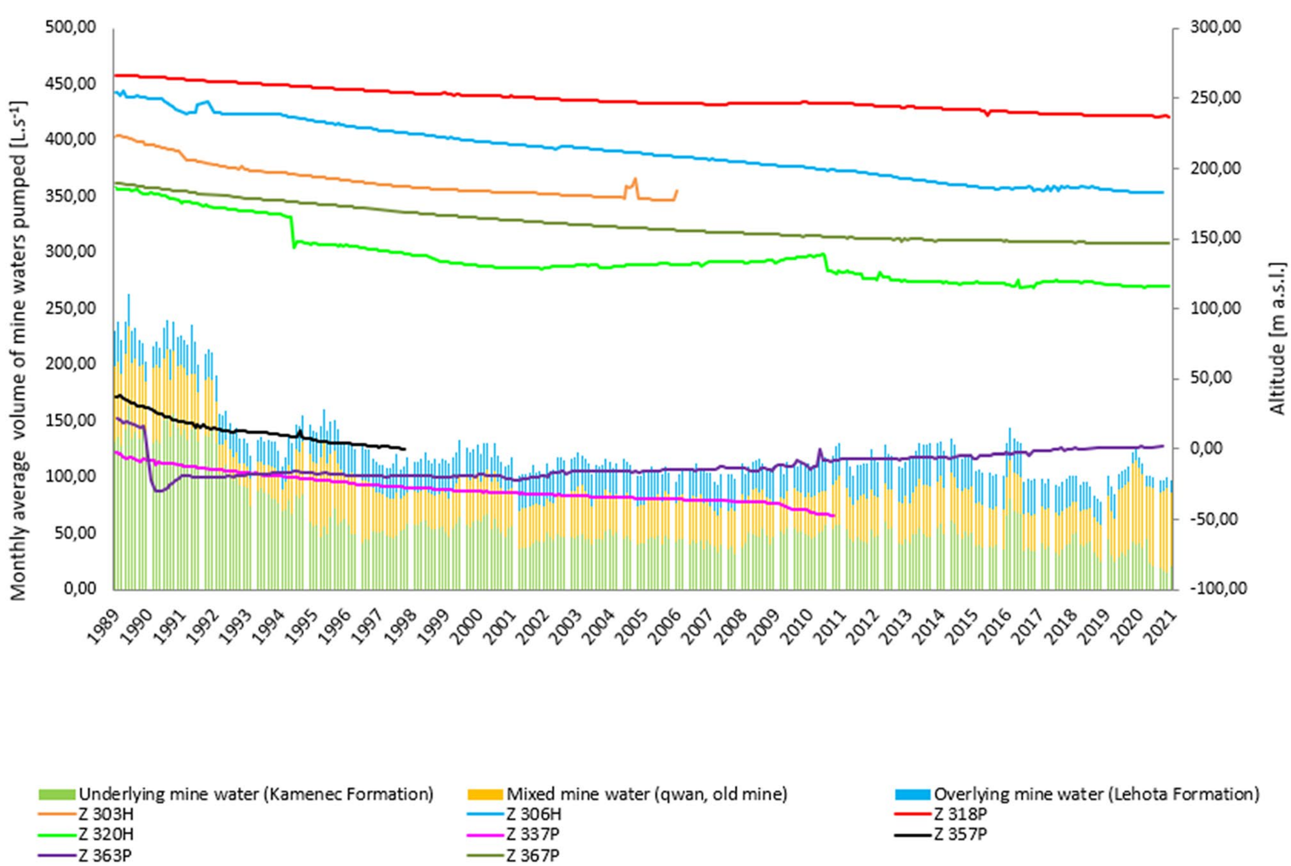

Fig. 5 Graph of average monthly pumped mining water in the Nováky coal deposit and the course of the water level in boreholes situated in the Kamenec formation for the period from January 1989 to December 2018 (modified from Borovicová 2020)

which was also confirmed by well Š1-NB II (Halmo et al. 2019a).

The genesis of the thermal water from the Bojnice High Block is different from that of the the Upper Nitra basin thermal water. A specific phenomenon occurs in this area because thermal water penetrates from the deep subsoil (water temperature of ≈ 60 °C) into the Bojnice High Block through delimiting faults at the level of the Middle Triassic and basal Paleogene. This saturation leads to an interesting hydraulic and hydrogeochemical phenomenon: the cooler shallower-circulation water mixes with the deeper-circulating water, thus creating the characteristics of the "Bojnice natural mix." This mixing has occurred since ≈ 1958 when surface drilling started in the Bojnice High Block (Halmo et al. 2019a). The natural intact state is still represented by the main springs of the Thermal Lake spring (14–18 L s^{-1}), Old spring (6–9 L s^{-1}) and Štrand spring (7–3.5 L s^{-1}). Of course, Bojnice's thermal springs have changed over time, especially in terms of quantity and location. The occurrence of travertines and springs, many of which have disappeared or diminished before 1980, are evidence of this (Rebro 1982).

Analysis of the Contact Zone Between the Nováky Coal Deposit and the Bojnice High Block

The question of the relationship between the Bojnice thermal water and the Nováky coal deposit became especially important in 1954, when in January there was an inrush of mine water of ≈ 10 L s^{-1}, with a temperature of 25 °C at the main trench of the 1st horizon of the Mládež mine (+ 80 m a.s.l.) After half a year, the yield ofthe Bojnice thermal springs decreased from 39 to 15 L s^{-1}. The aquifers were assumed to be hydrologically connected (Franko 1970).

Based on an analogy and contemporary knowledge about the geological structure with an overflow of thermal water from the wastes (exhausted areas) at the Döllinger mine (in 1879) in the Old Bohemian Coal District, Hynie (1963) admitted this possibility to the Nováky coal deposit owners. Hynie assumed that the Mesozoic formations of the Bojnice High Block and the Neogene and Paleogene formations of the Nováky Depression were interconnected at the main marginal Malá Magura fault (Fig. 6). The team came to the conclusion that coal mining in the deeper parts could endanger the Bojnice thermal springs (Hynie 1963). The situation of thermal springs and boreholes with thermal water in Bojnice High Block is shown in Fig. 7.

Franko also dealt with this relationship between 1961 to 1968, attempting to ensure maximum protection for the resources of the Bojnice spa, while also extracting the maximum amount of the alotted coal resources. Structural wells NB-1, NB-2, NB-3, Š1-NB (Fig. 3) and Š2-NB (Fig. 8) were drilled in the Bojnice High Block and the Upper Nitra basin to clarify the geological structures (Franko et al. 1968).

Franko (1970) retrospectively evaluated the 22 January 1954 mine water inrush using the most reliable measurements, which were at the source of the Old Spa spring. By analyzing the measurements of the springs at the Bojnice spa, he found that in 1954, the yield of all Bojnice springs decreased, except for Štrand spring (Fig. 7), which, in contrast, recorded a certain rise. This source is situated at the top and should have reacted more sensitively. He found that there had been similar declines and increases in the spring yield previously. Analyzing the precipitation records and the replenishment of the thermal water supplies and the time it took after precipitation events for the yield to increase brought new light to this issue. The main finding was that for the coldest areas (Štrand spring—Fig. 7), the randardation period was 2 months, with the maximum yield occurring at the end of May (or even June) and the minimum in November to February. The warmest temperatures (the Old Spa spring) had a randardation period of 9 months, with the maximum yield at the beginning of January and the minimum at the beginning of November. Relative to the mining of the Nováky coal deposit at the Bojnice High Block, he found that inflows of water into the mine did not increase until 1954, especially after 1958, when water began to be pumped from the 2nd horizon of the Mládež mine at an absolute height of − 50 m a.s.l. As a result, the pressure depression of the hydrostatic level around the shaft decreased by 135 m. This significant decrease was not recorded at the Bojnice springs, although the yield of the Bojnice geothermal springs occurred at the same time as the the mine water inrush in 1954 (39 L s^{-1}). Based on these findings, Franko (1970) concluded that the Paleogene sediments in the Bojnice High Block and in the Mesozoic overburden and in the subsoil of the coal seam in the Nováky coal deposit forms a planar, protective impermeable insulator against the pressurized thermal water in the Mesozoic carbonates.

During the last half century (1970–2020), the regime of the thermal water was clarified based on some new wells, along with the course of the Malá Magura fault and the geological conditions on its sides, which were determined from wells Š1-NB II, Š1-NB III, NB-4 až NB-11, BR-1, BR-2, BR-3, BR-6, Z-1, Z-3, Z-408, Z-409P and Š1-NB IV, based on the hydrophysical paramanders of carbonates from these wells (Dzúrik and Tomana 2016; Franko and Franko 2000; Halmo et al. 1994, 1997; Hók et al. 1995; Jezný et al. 1995; Vondráček et al. 1990). New maps have been developed illustrating the structural-tectonic scheme of the Preconosoic underlier, along with hydrogeological, geological, and geothermal maps. The new information confirmed existing knowledge about the permeability and impermeability of fractures in the mine. Also, the chemical composition of mine water from the underlying hydrogeological unit was analyzed.

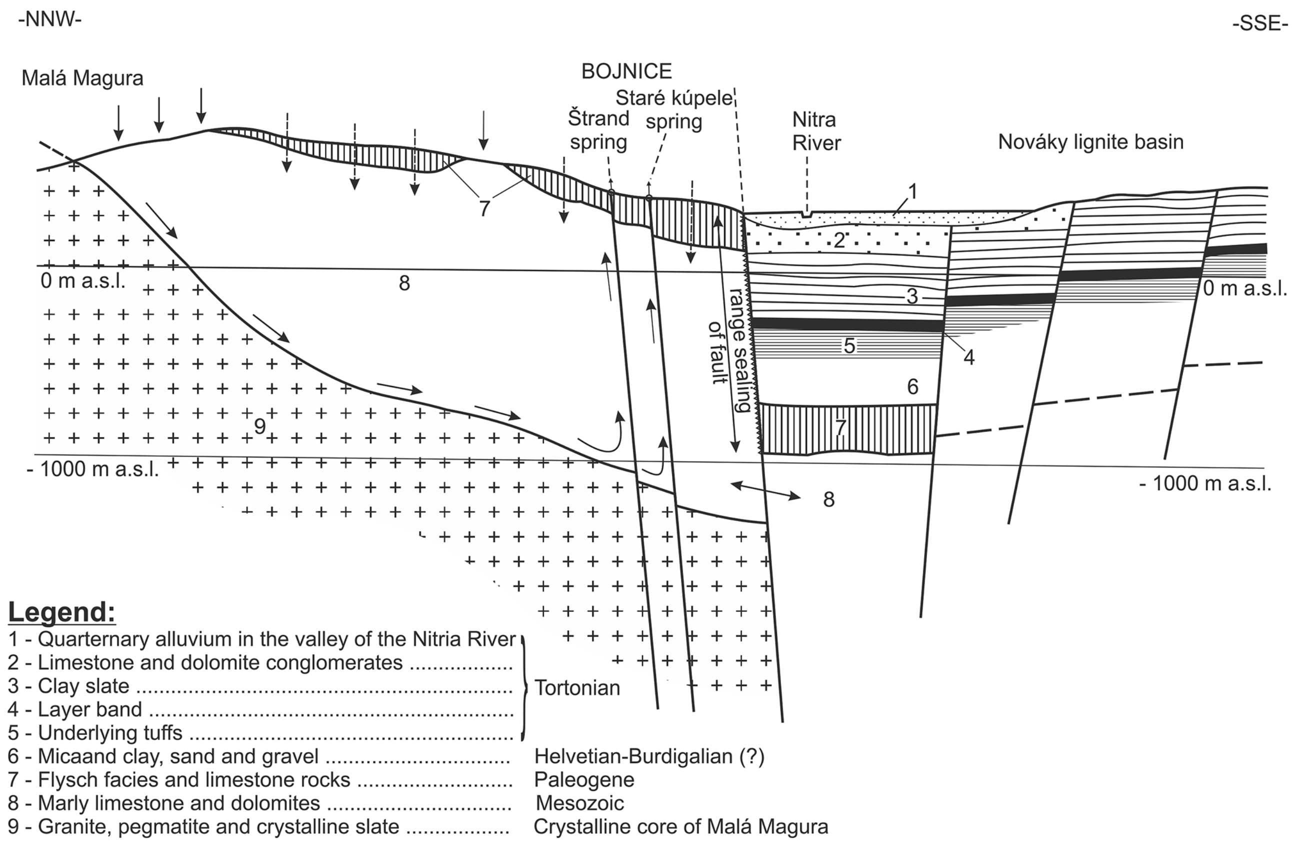

Fig. 6 Schematic section across the Bojnice High Block and the Nováky coal basin according to Hynie (1963)

New information on thermal water flow was also obtained based on long-term monitoring of the wells Š1-NB in village Koš and Š1-NB II in the former village of Laskár, as well as a long-term (June 2, 1993–August 12, 1994) overflow test on the well Š1-NB II and a pumping test Š1-NB IV in the former village of Púšt (April 19–July 25, 2016). The analytical model for Š1-NB II confirmed that the withdrawal of 20 L s^{-1} of water would not affect the Bojnice thermal water, and even confirmed that it was possible to draw another 25 L s^{-1} of thermal water from the accumulation area through two wells east of the Malá Magura fault, in addition to taking 20 L s^{-1} of water from borehole Š1-NB II (Jezný et al. 1995).

Also, detailed mathematical-statistical analysis excluded the possibility of water being suctioned through faults, especially from the Paleogene and Egenburg periods, and even from the Mesozoic. Based on these findings, the possibility of a slight overpressure of water, which was expected to take place very slowly during mining, was eliminated. Indeed, the assumption that water could flow from deeper layers into the underlying tuffs via the tectonic faults has not been confirmed (Halmo et al. 2001b).

Figure 8 shows the real distance between the Bojnice high block and the Novaky coal deposit. It was created on the basis of drilling survey and geophysical method of vertical electrical sounding (VES) (Fig. S-2). Shows that the Nováky deposit does not really rely on the Malá Magura fault, as Hynie (1963) (obr. 6) assumed.

Analysis of Quality and Quantity of Mining Water in Relation to Thermal Water

Quality Analysis

Three aquifer systems (overlying, underlying and Triassic layers) affect the Nováky coal deposit. However, the chemical composition of the mine waters indicates that the Triassic aquifer system was replaced by a newer mixed aquifer system, which arose as a direct consequence of the mining activity and directly connects with the overlying and underlying aquifer system.

Overlying aquifer system The groundwater of this aquifer system has accumulated in the detrital-volcanic strata (Lehota and Lelovec formations; Fig. 2), while its chemical composition depends mainly on the varied mineralogical composition of the strata sediments. A basic mathematical-statistical analysis of 60 examined samples indicate that the groundwater of the overlying dewatering system is

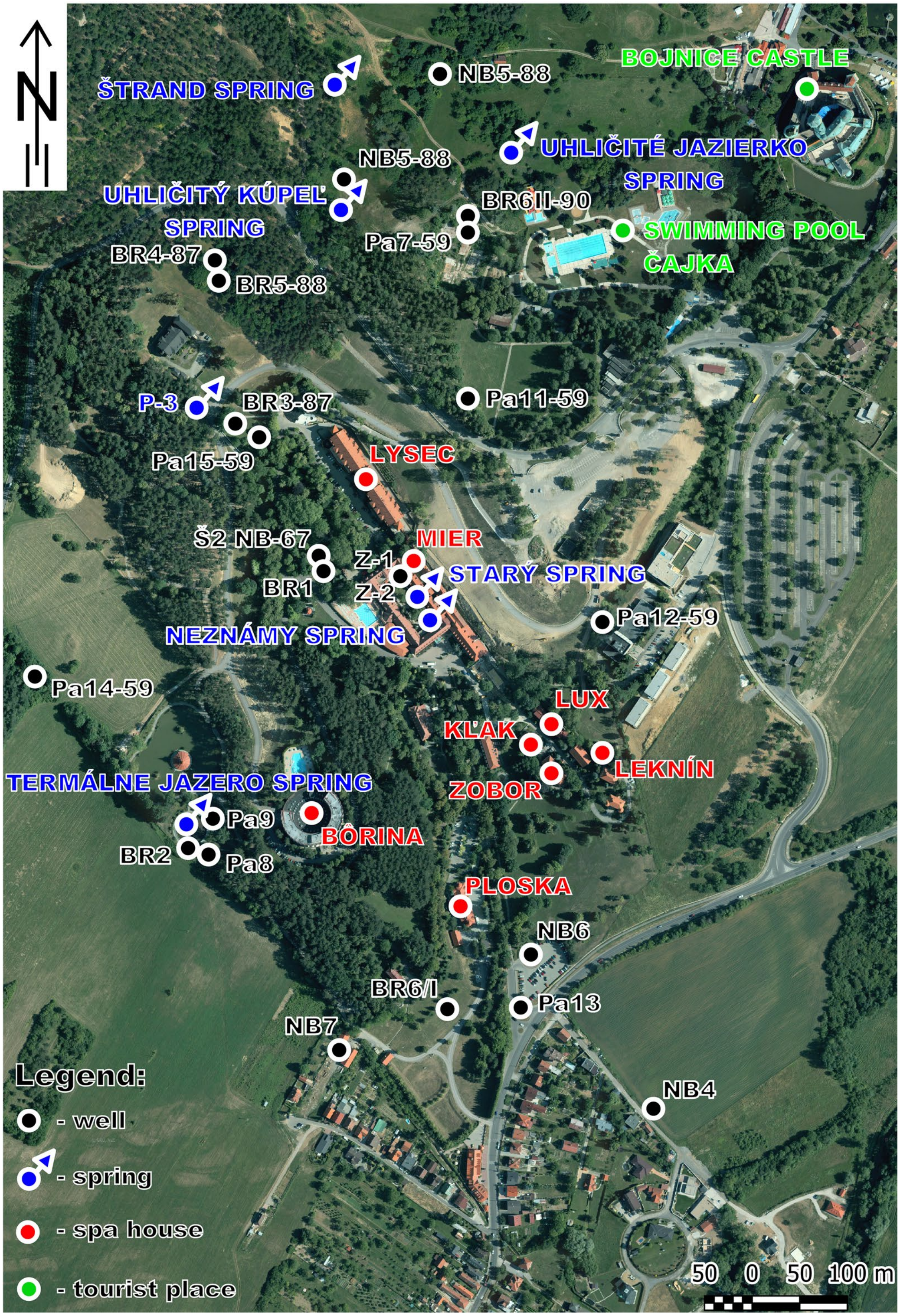

Fig. 7 Map showing the sources of thermal water in the Bojnice High Block (on the topographic basis of the Map Client ZBGIS® of the Geodesy, Cartography and Cadastre Authority of the Slovak Republic, link: https://zbgis.skgeodesy.sk/mkzbgis/)

characterized by the total amount of dissolved solids (TDS), ranging from 250 to 700 mg•L^{-1} of the Ca-Mg-HCO_3 chemical type (Table 2).

Underlying aquifer system This aquifer is connected with the stone formation (Fig. 2). The TDS of this system reaches 260–640 mg•L^{-1}, while the chemical type is Na-HCO_3, and

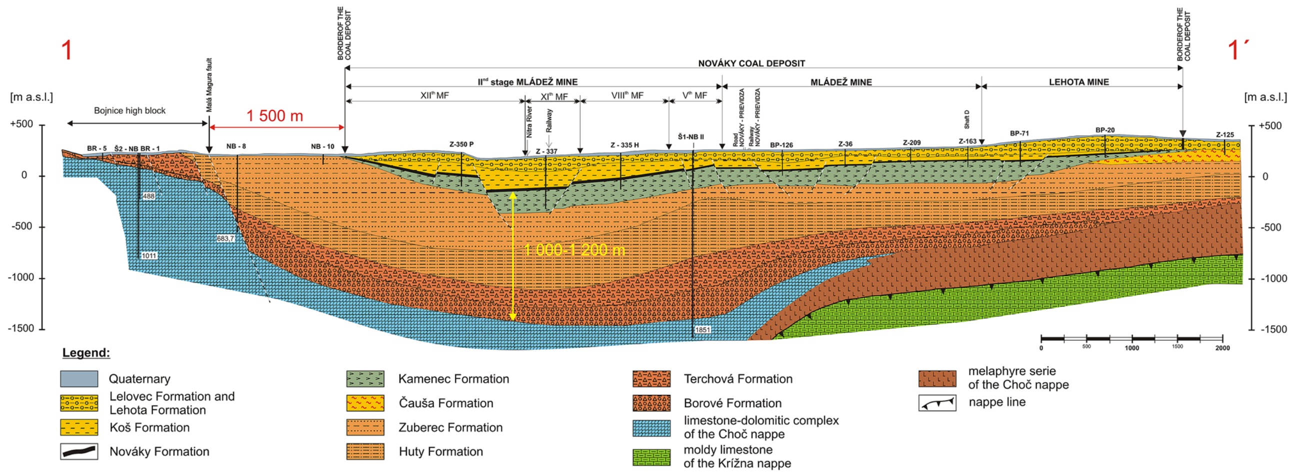

Fig. 8 Schematic hydrogeological section of Bojnice High Block and the Nováky depresion (Halmo et al. 2019b)

sometimes Na-Ca-HCO_3. The results of the statistical analysis of the 71 examined samples are summarized in Table 3:

The Nováky coal deposit was initially mined in all directions, though the main opening works were mostly mined in the Kamenec formation. Supplemental Fig. S-2, and Figs. 9, 10 and 11 show graphs of the of mine water analysis from selected wells that were drilled into the Kamenec formation (Fig. 2). The samples were selected to cover the entire area of the Nováky coal deposit (Fig. 12). The first graphic presentation (part "a") is from 2002, while part "b" contains graphic representations from different time periods. Part "b" shows the chemical analyses of the last sampling at a given location, which depends on the exploitation of the deposit (inaccessible parts). As it is clear from these graphs, the chemical composition of the groundwater remains unchan ged.

Mixed aquifer system Represents the most heterogeneous group of groundwater, because their occurrence is tied to the exhausted mining areas of the Gwan and Old mines. For this reason, they are characterized by increased mineralization (0.6–4.2 g•L^{-1}) and a high sulfate content due to oxidation of the dispersed sulfide phase (pyrite, realgar, arsenopyrite, auripigment), which was unevenly distributed in the coal seam. The water of the mixed aquifer is classified as sulfogenic groundwater, which was also indicated by the results of the mathematical-statistical analysis of 49 examined samples (Table 4).

Quantity Analysis

The distribution of mining fields and the size of the excavated mining area of the Nováky coal deposit (≈ 31 km^2) and the corresponding drainage of a significant volume of mine water (in the past between 6 and 7 million m^3 $year^{-1}$, currently between ≈ 3 and ≈ 4 million m^3 $year^{-1}$) required the construction of a large number of local and tentative pumping stations. Water from these pumping stations is then pumped to the main pumping stations, which are mainly located at an elevation of -45.0 m a.s.l. From the main pumping stations, the mine water is then pumped directly to the surface (+ 270 to + 300 m a.s.l.).

Measuring the groundwater levels within the surface boreholes helps explain the mutual relationships of the many dewatering systems over the past 30 years. These measurements are performed at intervals of usually at least once a month, on the basis of which it is possible to not only document drainage processes in the deposit, but also the development of groundwater levels in surface wells in the forefield of the Bojnice High Block.

As can be seen from Fig. 13, drainage of the deposit in the mining fields VII and XI (Fig. 1), which are the closest to the Bojnice High Cover, did not affect the development of piezometric groundwater level in the Kamenec formation (well Z 408P), or in the Čausa formation (well Z 409P) and the middle Triassic dolomites of the Bojnice High Block

Table 2 Results of statistical evaluation of chemical composition of the overlying groundwater system (Halmo et al. 2019b)

TDS mg L^{-1}	pH –	t °C	Na mg L^{-1}	K mg L^{-1}	Mg mg L^{1}	Ca mg L^{-1}	Fe mg L^{-1}	Cl mg L^{-1}	NO_3 mg L^{-1}	SO_4 mg L^{-1}	HCO_3 mg L^{-1}
347.68	7.48	12.25	37.17	21.73	21.71	56.05	0.02	14.06	0.17	48.9	324.75

TDS total dissolved solids (mg L^{-1}), *t* average water temperature (°C)

Table 3 Results of statistical evaluation of the chemical composition of the underlying groundwater system (Halmo et al. 2019b)

TDS $mg\ L^{-1}$	pH –	t °C	Na $mg\ L^{-1}$	K $mg\ L^{-1}$	Mg $mg\ L^{1}$	Ca $mg\ L^{-1}$	Fe $mg\ L^{-1}$	Cl $mg\ L^{-1}$	NO_3 $mg\ L^{-1}$	SO_4 $mg\ L^{-1}$	HCO_3 $mg\ L^{-1}$
434.17	7.89	25.78	115.46	63.31	8.14	18.27	0.02	36.53	0.01	50.06	376.46

TDS total dissolved solids ($mg\ L^{-1}$), *t* average water temperature (°C)

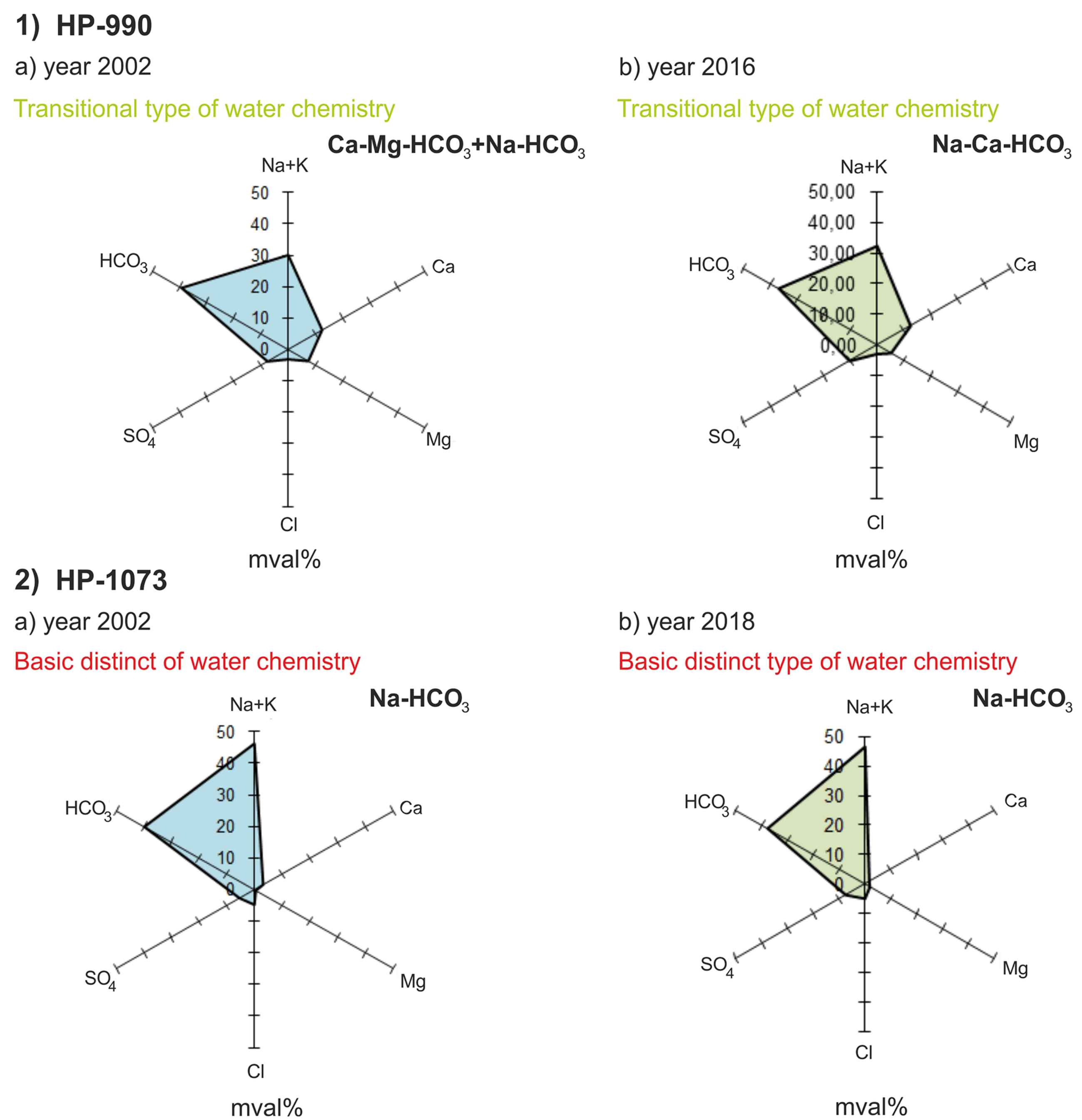

Fig. 9 Graphs comparing selected samples from the Kamenec formation in the northern part of the Nováky coal deposit (Borovicová 2020)

(wells NB-1, NB-4, NB-5, NB-7 and NB-8) (Fig. 3). The groundwater level at the surface wells NB1, NB-4, NB-5, NB-6, NB-7, and NB-8 has not changed significantly over the last 30 years and there has been no dramatic changes

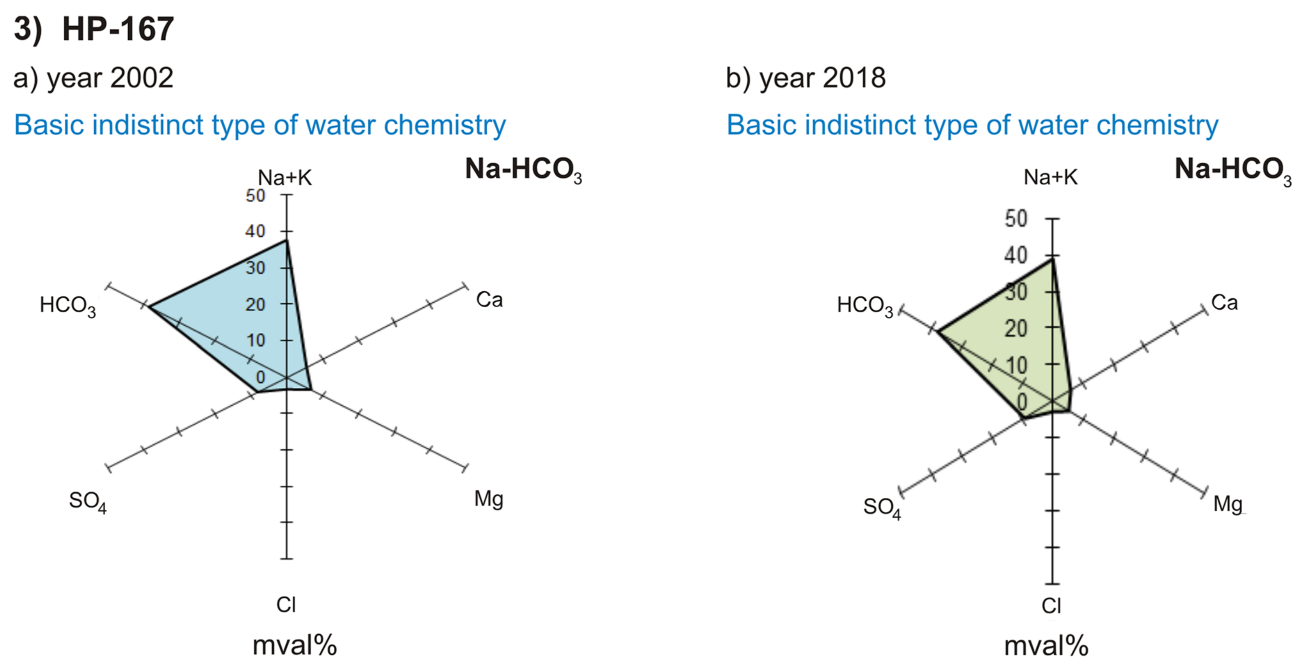

Fig. 10 Graphs comparing selected samples from the Kamenec formation in the central part of the Nováky coal deposit (Borovicová 2020)

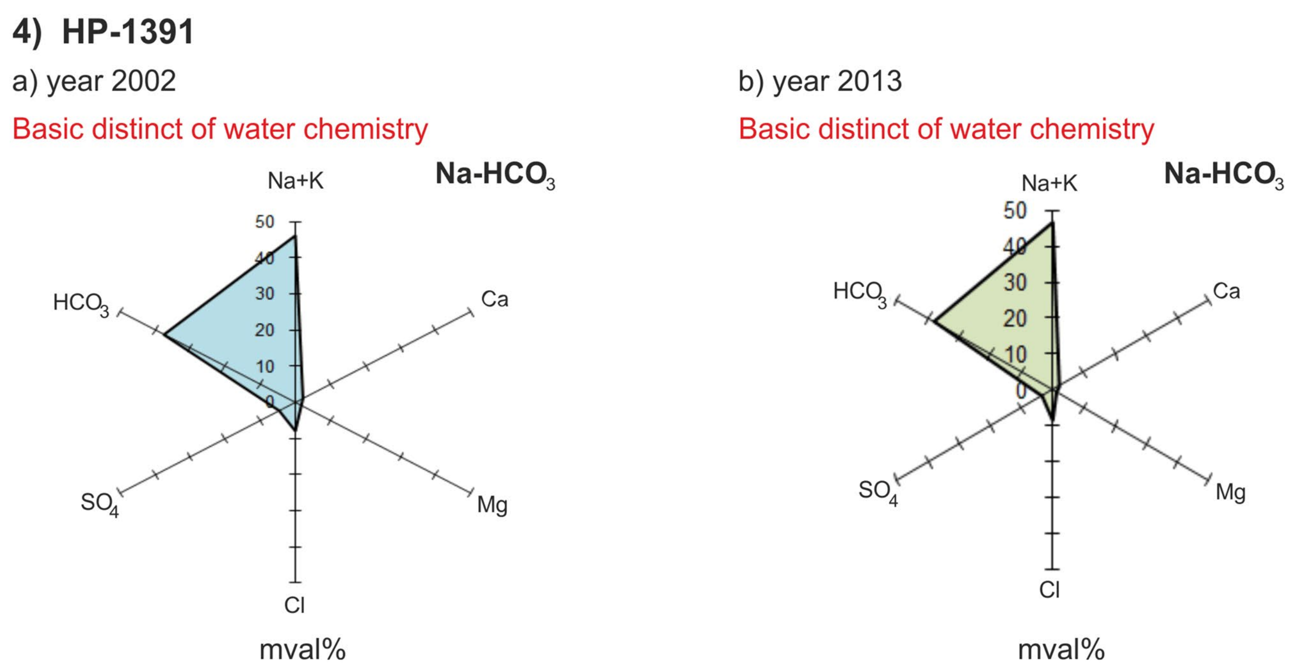

Fig. 11 Graphs comparing selected samples from the Kamenec formation in the southern part of the Nováky coal deposit (Borovicová, 2020)

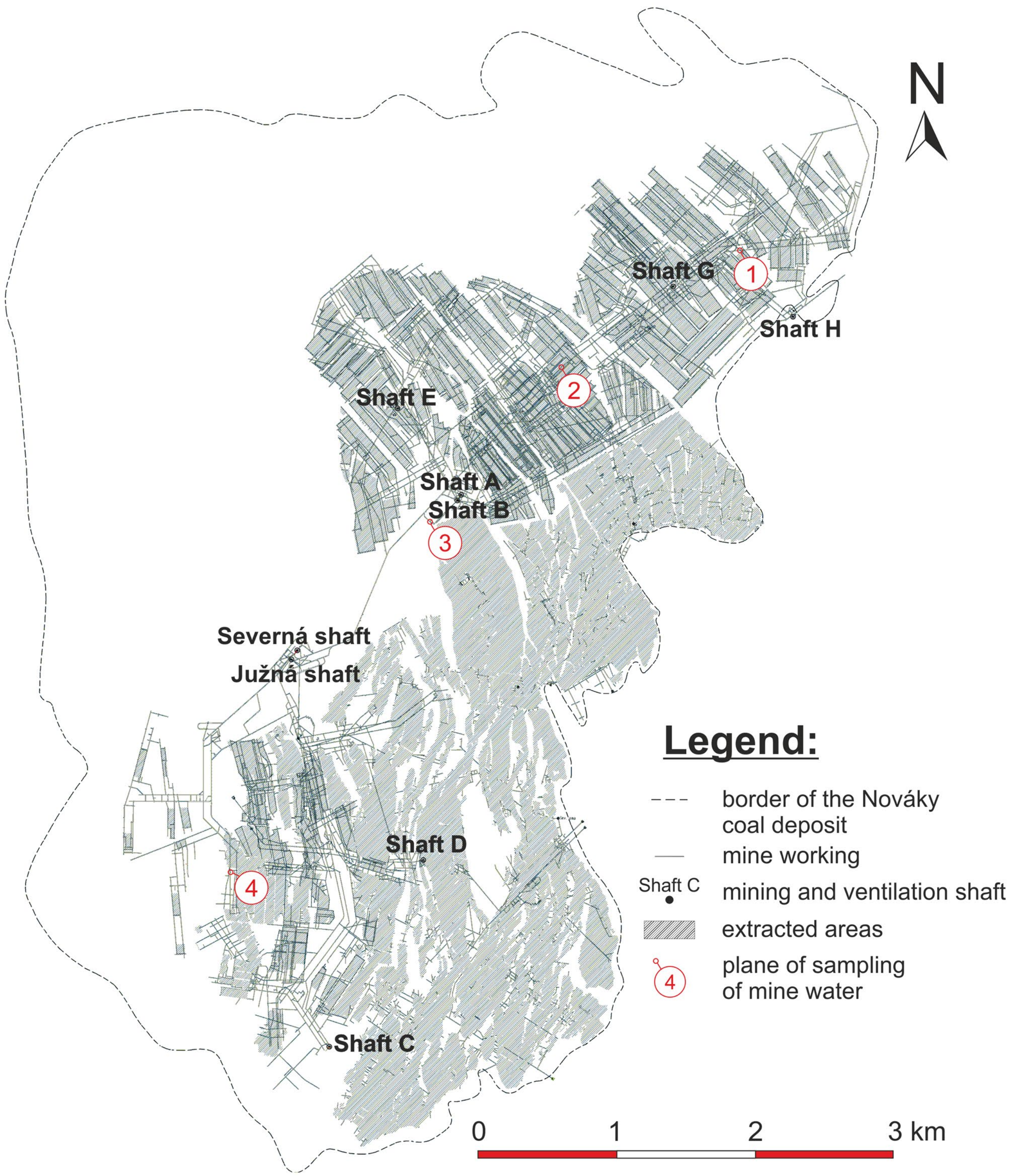

Fig. 12 Map of the Nováky coal deposit showing groundwater sampling points

in the groundwater level (Fig. 13) that could be linked to the mining activities in the Nováky deposit or mining of the VII and XI mining fields. For example, in well NB-5, the groundwater level recorded in 1988 was at an altitude of + 327.94 m a.s.l., while in 2018, it was at + 321.76 m a.s.l., which means that the groundwater level in this well had fallen by 6.18 m.

Rebro (1982) provides comprehensive information on the abundance of thermal resources in the area of the Bojnice High Block over many decades. From this work, it is clear

Table 4 Results of statistical evaluation of chemical composition of the mixed mine water (gwan water, water of old mine) (Halmo et al. 2001b)

TDS $mg\ L^{-1}$	pH –	t °C	Na $mg\ L^{-1}$	K $mg\ L^{-1}$	Mg $mg\ L^{1}$	Ca $mg\ L^{-1}$	Fe $mg\ L^{-1}$	Cl $mg\ L^{-1}$	NO_3 $mg\ L^{-1}$	SO_4 $mg\ L^{-1}$	HCO_3 $mg\ L^{-1}$
1401.2	6.85	17	105.5	31.2	49.7	180.9	0.49	33.7	0.25	262.6	735.8

TDS total dissolved solids (mg L^{-1}), *t* average water temperature (°C)

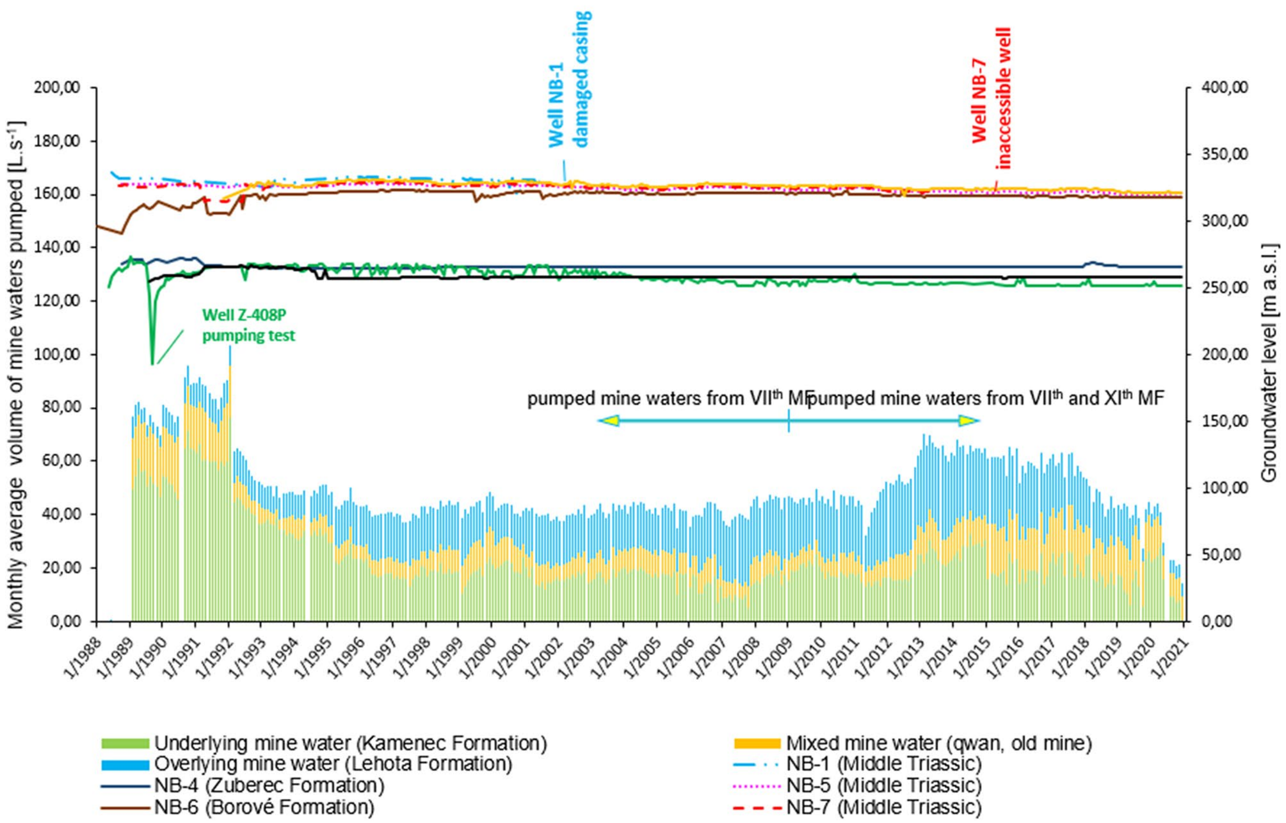

Fig. 13 Graph of average monthly pumped mine water from the mining fields VII and XI in the Nováky coal deposit and the course of the level in the wells Z 408P, Z 409P, NB-1, NB-4, NB-5, NB-6, NB-7, and NB-8 for the time period between January 1988 and December 2018 (summarised from Borovicova 2020)

that the yield of the Termálne jazero (literal translation: Thermal Lake) spring decreased by 63.15% between 1945 and 1980, from 32.22 to 11.87 L•s^{-1} in 1980 (Fig. 14). From the data available in the literature on the yield of the Termálne jazero spring (Franko et al. 1968; Jezný et al. 1995; Rebro 1982; Urban 1960; measurements performed by the hydrogeological service of the company Hornonitrianske bane Prievidza, a.s.) diagrams of annual yield averages for the years since 1945 were compiled. As shown in Fig. 14, an obvious diverging trend of the Termálne jazero spring, which is approximated by the linear equation $y = -0.0007x + 31.766$ with a regression coefficient of $R^2 = 0.8551$. The given diagram was then compared with the total volumes of pumped mining water from the Nováky mine for the years from 1954 to 2020. By comparing these two diagrams, we find that it is possible to clearly exclude any individual or group correlations of the two. This means that the dewatering of the Nováky coal deposit had nothing to do with the decreased yield of the Termálne jazero spring.

At the same time, there is an obvious increase in the yield of the Termálne jazero spring in 2020, which is directly related to the occurrence of the COVID-19 virus in Slovakia. As part of the preventive measures, the Bojnice spa was completely closed from April to May 2020. Then, from May to June 2020, only spa guests with prescriptions were allowed to come, and only on a limited basis. From June to October 2020, the Bojnice spa was put back into full mode operation, but then returned to limited operation again in October 2020, which now continues a year later. This mode

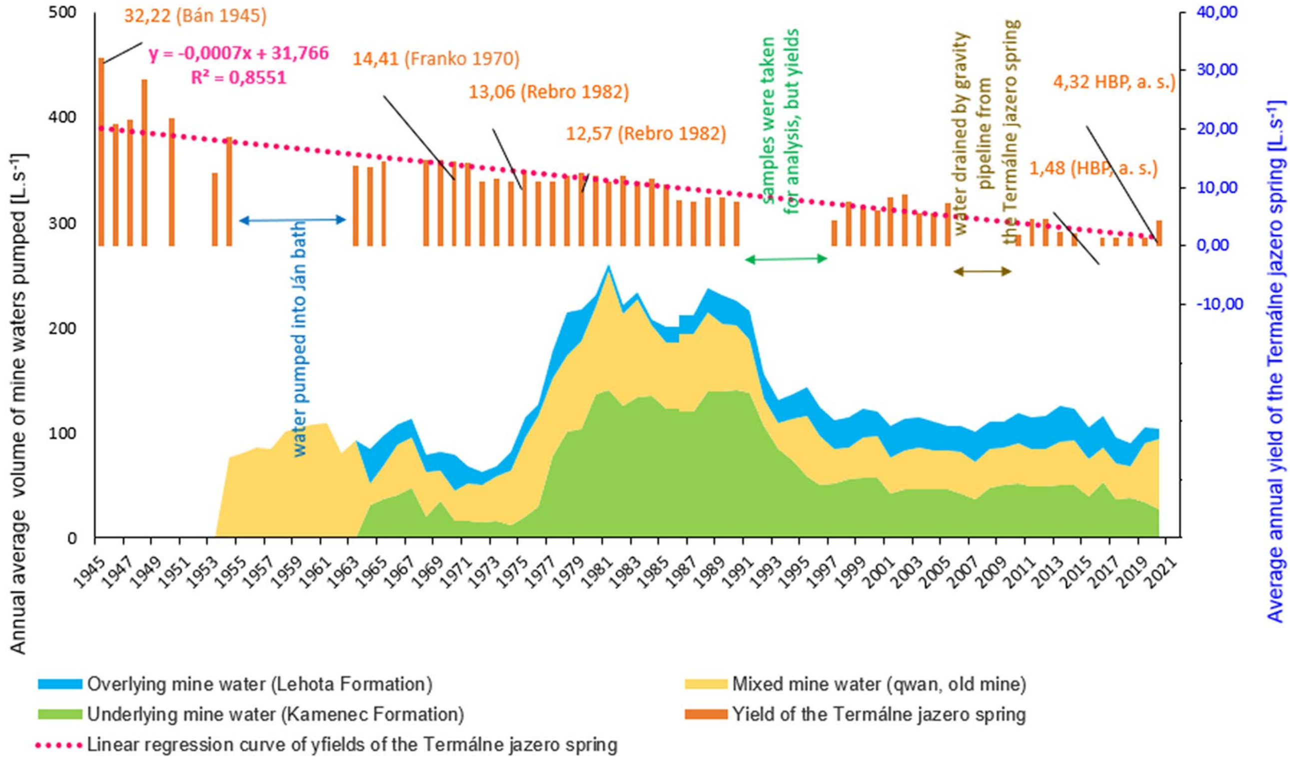

Fig. 14 The course of yield for the Termálne jazero spring relative to the average annual quantities of pumped mining water in the Nováky mine for the period of January 1945 to December 2020 (adjusted according to Halmo et al. 2019a)

of operation decreased extraction of thermal water in the Bojnice High Block area, causing flow of the Termálne jazero natural spring to increase.

The abundance of springs in the Bojnice High Block area is demonstrably influenced by the pumping of thermal water. Čaučík et al. (2018) showed that the balance of resource use of Z-2 (Old spring), BR-1 (Jesenius) and Termálne jazero (Fig. 7) was satisfactory. The balance of resource use of Z-1, Pa-7, BR 6, BR-3, BR-4, and BR-5 (Fig. 7) was assessed as good, but the balance of use at BR-2 (Fig. 7) was critical. Vrána et al. (2011), Vandrová (2000) and Dzúrik and Tomana (2016) point out in their final reports that the irrational pumping of thermal water has been taking place for a long time in the area of the Bojnice High Block. Sources of thermal water in the Bojnice High Block, such as Pa-7 and PB-6, which are not declared as natural healing sources, are uncontrolled, and are especially used during the summer season for the Čajka recreational swimming pool (Vandrová 2000). At the same time, sources BR-1, BR-2. and Z-2 (Fig. 7) greatly exceeded their permitted consumption limit (Dzúrik and Tomana 2016).

Summary and Conclusion

The natural state of the intact Bojnice High Block is represented by outflows at the Termálne jazero spring (14–18 L s^{-1}), the Old spring (6–9 L s^{-1}), and Štrand spring (7–3.5 L s^{-1}). Of course, the Bojnice thermal springs have changed over time; many have disappeared, and their productivity was in decline even before 1980 (Rebro 1982). At present, there is only one original spring from the Bojnice High Block springs—the Termálne jazero spring.

The relationship between the Nováky coal deposit and Bojnice's thermal water resources began to be investigated back in 1954 when there was an inrush of 25 °C water of ≈ 10 L s^{-1} at the main trench of the 1st horizon (+ 80.00 m a.s.l.) of the Mládež Mine. Half a year later, the yield of the Bojnice thermal springs decreased, raising fears that a large groundwater depression in the Kamenec formation caused by the mining operations might be draining water from the Bojnice spring structure. However, by analyzing the measurements of the springs in the Bojnice spa, Franko (1970) found that in 1954, the yield of all Bojnice springs decreased, except for Štrand spring, which recorded a certain rise, which appeared to contradict a relationship between the two events. Indeed, Franko found that in 1958, water being pumped from the 2nd horizon of the Mládež mine at an elevation of -50 m a.s.l caused the hydrostatic level near the shaft to decrease by 135 m. However, this decrease was not recorded at the Bojnice springs, although at that time the yield of the Bojnice terrains was the same as at the time of the flood in 1954. Based on these findings, Franko (1970) concluded that the Paleogene sediments form an almost impermeable barrier against the pressurized thermal water in the Mesozoic carbonates. These sediments have been found in the Bojnice High Block in the Mesozoic overburden and in the subsoil of the coal seam in the Nováky coal deposit.

The theory of water being suctioned by the faults was also refuted by the results of a detailed mathematical-statistical analysis. The hypothesis that there may be direct inflows of water from deeper areas into the underlying tuffs after tectonic faults was also not confirmed (Halmo et al. 2001b). At present, we can state that even after formation of a deep depression (≈ 550 m) in the Kamenec formation, there was no manifestation of thermal water being suctioned from the Triassic aquifer system. And now, with the decline of mining from the deepest parts of the deposit, there has been a gradual revitalization of the original hydrogeological conditions in the Kamenec formation.

In addition, an analysis of the contact zone confirmed that the Kamenec formation and the wedged Nováky coal deposit are far enough from the Malá Magura fault to rule out any lateral penetration from the Bojnice thermal water into the mining areas. At the same time, an analysis of the quality of the mine water refuted the possibility of even slight suctioning of thermal water from the Triassic aquifer sytem, as the chemical composition of the Kamenec formation groundwater has not changed over time.

In conclusion, it can be stated that in a significant area of Slovakia, there has been a decrease in groundwater resources and reserves since 1980, most likely due to climate change. Vrána et al. (2011) states that the average yields of long-monitored sources of the the Slovak Hydrometeorological Institute decreased, on average by 12.7% (median – 16.9%) from 1980 to 2010. Since the quantity of useable thermal water water is not currently determined by acreage, it is not possible to update this figure. However, it is necessary to account for the natural decrease in quantity, which is most likely due to changes in climatic conditions. At the same time, several authors have observed that the irrational pumping of thermal water has been occurring for a long time in the Bojnice High Block area.

Supplementary Information The online version contains supplementary material available at https://doi.org/10.1007/s10230-022-00848-9.

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