Mine Water Environ (2017) 36:4–17
DOI 10.1007/s10230-016-0420-6

TECHNICAL ARTICLE

Regional Impact of Uranium Mining on Piezometric Surfaces in a Multi-layered Water-bearing System, Bohemian Cretaceous Basin, Czech Republic

Tomáš Lipanský[1]

Received: 14 June 2016 / Accepted: 29 September 2016 / Published online: 25 October 2016

Abstract The former mining of uranium in Cenomanian sandstone sediments has had a tremendous impact on natural groundwater flow in a multilayered water-bearing system within both the Bohemian Cretaceous Basin and the Czech Republic. Newly created graphs and maps of piezometric surfaces provide insight into the dynamics of the basin′s water-bearing system and give an idea of long-term groundwater heads and flow directions in the area, despite the fact that this study was simply an interpolation of monitoring data. Maps and grids of piezometric surfaces were used to calibrate hydraulic models. The piezometric surface of the Cenomanian aquifer in the Stráž block was lowered by 170 m by underground uranium mining, with the affected area extending more than 50 km along the regional flow direction. The extent of the piezometric surface affected (600–700 km^2) is much larger than the area directly affected by the chemicals that were used for acid in-situ leaching (24–27 km^2). Other aquifers, especially the Turonian aquifer, which is widely used as a water supply, have not been seriously affected. At the current rate of flooding of the residual depression, the piezometric surface may reach the pre-mining state within several decades. The possibility of returning to the natural groundwater regime in the in-situ leaching area and its forefield depends on the remediation technology that will be used at those sites in the future. Such an extensive intervention into the groundwater regime has to be seen in context of its long-term development. Based on the recorded far-reaching influence of mine dewatering and flooding on the piezometric surface of the Cenomanian aquifer towards the southwest, it is appropriate to refer to the entire Boleslav–Mělník water-bearing system adjacent to the Středohoří fault zone (from the infiltration area at Lužice fault to the drainage area in the Labe river valley) as the Stráž block.

Keywords Long-term groundwater monitoring · Piezometric head development · Mine dewatering and flooding · Stráž block · Inter-aquifer leakage

Introduction

Uranium (U) resources have been found around the world in manifold geologic formations and deposit types. Many of them have been or are still being extracted using techniques such as classic underground or open-pit mining and in-situ leaching (ISL). Numerous articles have been published describing their geology, mineralogy, mining techniques, economic or environmental aspects as groundwater geochemistry, contamination, and remediation (e.g. Adams and Younger 2001; IAEA 1993, 2005a; Merkel et al. 2002; Robertson et al. 2016; Taylor et al. 2004; Wolkersdorfer and Bowel 2005; Zielinski et al. 2007). Dewatering and consequential flooding of mine sites in various countries has been also described, mainly focused on the mine site itself or its close surroundings (IAEA 1993, 2005a; Jakubick et al. 2002; Merkel 2002; Merkel et al. 2002; Paul et al. 2006). However, the regional extent and long-term development of mining's impact on groundwater levels and flow directions

Electronic supplementary material The online version of this article (doi:10.1007/s10230-016-0420-6) contains supplementary material, which is available to authorized users.

✉ Tomáš Lipanský
tomas@watersystem.cz

[1] Charles University in Prague, Faculty of Science, Institute of Hydrogeology, Engineering Geology and Applied Geophysics, Albertov 6, 128 43 Prague 2, Czech Republic

is rarely mentioned in scientific articles, despite the fact that its extent may be significantly more widespread than the geochemical changes in groundwater, especially in multi-layered sedimentary basins.

The U resources in the sandstone sediments of the Bohemian Cretaceous Basin are situated at the base of a multi-layered water-bearing system, where both classical underground mining and ISL from the surface were conducted beneath the main Cretaceous aquifer, which is widely used as a communal water supply (Herčík et al. 2003). This mining greatly affected the natural groundwater flow of the Bohemian Cretaceous Basin and represents the largest human impact to groundwater in the Czech Republic.

In a similar hydrogeologic environment, another U resource was mined in the basal aquifer of the Cretaceous Basin in Königstein near the city of Dresden, Germany, by conventional room-and-pillar and underground acid ISL (Jenk et al. 2014; Klinger et al. 2000; Merkel 2002; Paul et al. 2013). Nevertheless, the regional extent and development of groundwater levels has not been satisfactorily described, even for this site.

The U resources in the northern part of the Bohemian Cretaceous Basin were found by accident in 1962 during well-logging of a borehole situated in an anomaly found by an airborne magnetometry. From 1963 to 1967, eight U ore deposits were delimited. Three of the deposits were mined—the Hamr pod Ralskem deposit (Mine Hamr I—MH I, Mine Hamr II—MH II), the Břevniště deposit (Mine Křižany—MK I), and the Stráž pod Ralskem deposit (in situ leaching—ISL) between 1965 and 1996, with a total production of 30,000 t of U concentrate (Datel and Ekert 2008; Kafka 2003).

The environmental impacts of acid ISL in the Stráž deposit on groundwater chemistry and possible remediation techniques have been previously discussed (e.g. Balatka et al. 2006; Datel and Ekert 2008; Ekert 2008; Ekert and Mužák 2010; IAEA 2005a, b; Krásný et al. 2012; Lusk 1998; Mužák 2008; Novák 2001; Pačes et al. 2008; Slezák 2001; Smetana et al. 2002). Nonetheless, the development of the piezometric head decline caused by decades of dewatering underground mines and consequential flooding of closed mines has not been fully described, despite the fact that several flow and contaminant transport models have been published (e.g. Čermáková 2002; Datel 2009; Herčík and Kůrka 1990; Hokr et al. 2004; Lietava 2000; Novák et al. 2000, 2002; Novák 2001; Novák and Mužák 2002).

The area described in this paper extends from the Ještěd Ridge in the northeast to the Labe River valley in the southwest and the Jizera River valley in the southeast. The area represents an irregular rectangle with an elongated NE-SW axis, ca. 60 × 45 km, and is tectonically limited by the Lužice fault (LF) and the Labe and Jizera fault zones. The northwestern limit is set approximately by a line from Litoměřice to the municipality of Hrádek nad Nisou (Fig. 1). The U ore deposits are situated in the northeastern part of the area of interest.

This paper does not present a regional hydraulic model, but an interpretation of piezometric data. The maps and grids of the piezometric surfaces can be used to calibrate hydraulic models of the investigated area.

Geology and Hydrogeology

Lithostratigraphy

The Bohemian Cretaceous Basin is the largest groundwater reservoir in the Bohemian Massif, covering an area of 14,600 km^2, of which 12,490 km^2 lies within the territory of the Czech Republic and a minor part reaches into Germany and Poland. The basin is elongated in a NW–SE direction, is 290 km long, and up to 100 km across (Krásný et al. 2012). The surveyed area lies in the northern part of this basin (Fig. 1). A general outline of its stratigraphy, structural settings, and groundwater bodies is presented in Fig. 2.

The flat pre-Cretaceous basement consists of a Permo-Carboniferous volcano-sedimentary complex and the granitic and metamorphic crystalline complex of the Lugian and Saxothuringian areas (Skácelová et al. 2011; Valečka 2009). The basement and Cretaceous basin fill were later vertically differentiated by alpine foreland tectonics.

The Cretaceous basin fill, which accumulated from the Early Cenomanian or even Late Albian to the Santonian period, is composed of detrital sediments of variable grain size, and are divided into six lithostratigraphic units—from the oldest to the youngest: Peruc–Korycany, Bílá Hora, Jizera, Teplice, Březno, and Merboltice formations. The preserved thickness is usually between 200 and 400 m, with the greatest values (1000–1100 m) recorded in the vicinity of Děčín (Herčík et al. 2003).

The basal Cenomanian sequence of the Peruc–Korycany Formation is typically 70–80 m thick near the LF (max. 100–120 m) and gradually thins to 10–25 m towards the Labe River valley. Locally, it is missing over elevated basement, and is dominated by psammites of terrestrial, near-shore, or shallow marine origin (Uličný et al. 2009b), which form the basin-wide Basal Cenomanian aquifer. The lithologically prominent boundary between the Peruc–Korycany and Bílá Hora Formations corresponds with the Cenomanian/Turonian boundary.

The younger marine fill is characterized by two facies: quartzose sandstones of variable grain size, with fluctuating content of matrix or cement, which act as the main Turonian and Coniacian aquifers; and calcareous claystones to marlstones, and less frequently carbonate rocks, which act as (semi)aquitards.

The recently developed detailed differentiation of individual sedimentary cycles within the Cretaceous formations (Uličný 2001; Uličný and Laurin 2001; Uličný et al. 2009a, b) has no serious importance for this work, especially because most of the monitoring wells (piezometers) are open through the entire thickness of the Cenomanian and Turonian sandstone aquifers and thus do not allow any differentiation of groundwater piezometric heads in the individual sedimentary cycles.

Structure

The LF, which forms the NE border of the Bohemian Cretaceous Basin, is a major deep-reaching structure of the Variscan Elbe fault system, which was activated as a thrust fault in the late Cretaceous to Paleogene times, accommodating the uplift of the Sudetic block and contributing to significant crustal shortening in the Alpine foreland. In general, the LF separates the Neoproterozoic to lower Paleozoic Krkonoše–Jizera crystalline complex and the Lužice Pluton in the north from the sedimentary and volcanic rocks of the Late Paleozoic basins and the Bohemian Cretaceous Basin in the south. The relative position of the two wall blocks separated by the LF is compatible with reverse faulting, with a vertical displacement in excess of 1000 m. The real displacement is possibly much higher, since over 3.6 km could have been eroded from the hanging wall block of the LF since the Turonian (Coubal et al. 2014).

Another main fault zone of prime importance to the study area is the České Středohoří fault zone (CSFZ; Cajz et al. 2004), forming the southeastern limit of the Ohře/Eger rift graben and dividing the study area into two main water-bearing systems. This tectonic zone is dominated by NE–SW faults dipping steeply NW. These are right-laterally displaced by faults striking E–W, especially in its NE reach. Vertical displacement on the CSFZ has been calculated at 400–700 m (Cajz et al. 2004). The CSFZ and especially its northeastern part, the Stráž fault zone, runs roughly NE–SW, from the Ještěd Ridge to the Labe River valley, dividing the area of interest into two tectonic blocks.

The part southeast of the Stráž fault zone is called the Stráž block, which has an elevated crystalline basement (Skácelová et al. 2011). The Stráž block is tectonically defined within Upper Cretaceous sediments—in the NW by the Stráž fault zone and in the NE by tectonic contact with the crystalline hard-rock units of the Lužice fault zone, which defines the NE boundary of the Bohemian Cretaceous basin. The SE border of the Stráž block is formed by an area of neo-volcanic veins called Devil Walls. The southwestern border of the Stráž block is not clearly hydrogeologically or tectonically defined. The Hradčany fault, limiting the Stráž block on the southwest (IAEA 2005b; Smetana et al. 2002), has only been observed in the crystalline bedrock, not in the Cretaceous sediments (Kozáková and Pokorný 2009). The Stráž block belongs to the Boleslav–Mělník water-bearing system.

The part NW of the Stráž Fault Zone is called the Tlustec block, which belongs to the Benešov–Ústí water-bearing system. Only the part of Benešov–Ústí water-bearing system with a simple tectonic setting (Cajz et al. 2004), adjacent to the Stráž fault, is described in this work.

The upper Cretaceous sediments of the central part of the Stráž block are up to 300 m thick, while SE of the Devil Walls zone towards the Jizera River, the sediment thickness increases up to several 100 m. The situation is different in the Tlustec block, where Cretaceous sediments up to 1000 m thick are preserved.

Aquifers and Groundwater Bodies

Large sandstone bodies form aquifers with continuous groundwater flow in this part of the Bohemian Cretaceous basin. The aquifers lie mostly sub-horizontally. Major fault structures divide and limit the aquifers in the area of interest.

There four main aquifers within the Bohemian Cretaceous basin are the: Basal Cretaceous Aquifer A, largely associated with sandstones of the Peruc–Korycany Formation, locally also the Bílá Hora Formation (AB); Aquifer B in sandstones of the Bílá Hora Formation; the Main Cretaceous Aquifer C in the Jizera Formation sandstones; and the locally significant Aquifer D in the Teplice and Březno Formations (Herčík et al. 2003; Krásný et al. 2012). Aquifer C is the most significant for water supply purposes, providing 52 % of the basin's groundwater resources. Aquifers A (20 %), B (14 %), and D (14 %) are less important (Herčík et al. 2003). From a regional perspective, the area of interest lies on the border between two water-bearing systems: the Boleslav–Mělník system in the southeast and the Benešov–Ústí system in the northwest (Krásný et al. 2012).

Due to the dissimilar thickness of preserved Cretaceous sediments on each side of the Stráž fault, the number of Cretaceous formations and consequently, of hydrogeological bodies, aquifers and aquitards, is different in each water-bearing system. The Boleslav–Mělník system contains only part of the lower Cretaceous sequence, consisting of the Peruc–Korycany, Bílá Hora, and incomplete Jizera Formation, while the Benešov–Ústí system is the only part of the Bohemian Cretaceous Basin with all of the lithostratigraphic units from the Peruc–Korycany to the Merboltice Formation, many of them very thick.

In the area of interest described in this work, there are two aquifers associated with psammitic evolution of Cretaceous sediments in the area of interest in both the Stráž and Tlustec blocks: the Cenomanian (Basal) Aquifer A, with a hydraulic conductivity (K) that ranges from 1×10^{-6} to 5×10^{-5} m s^{-1}, a mean effective porosity of 0.18 (Datel

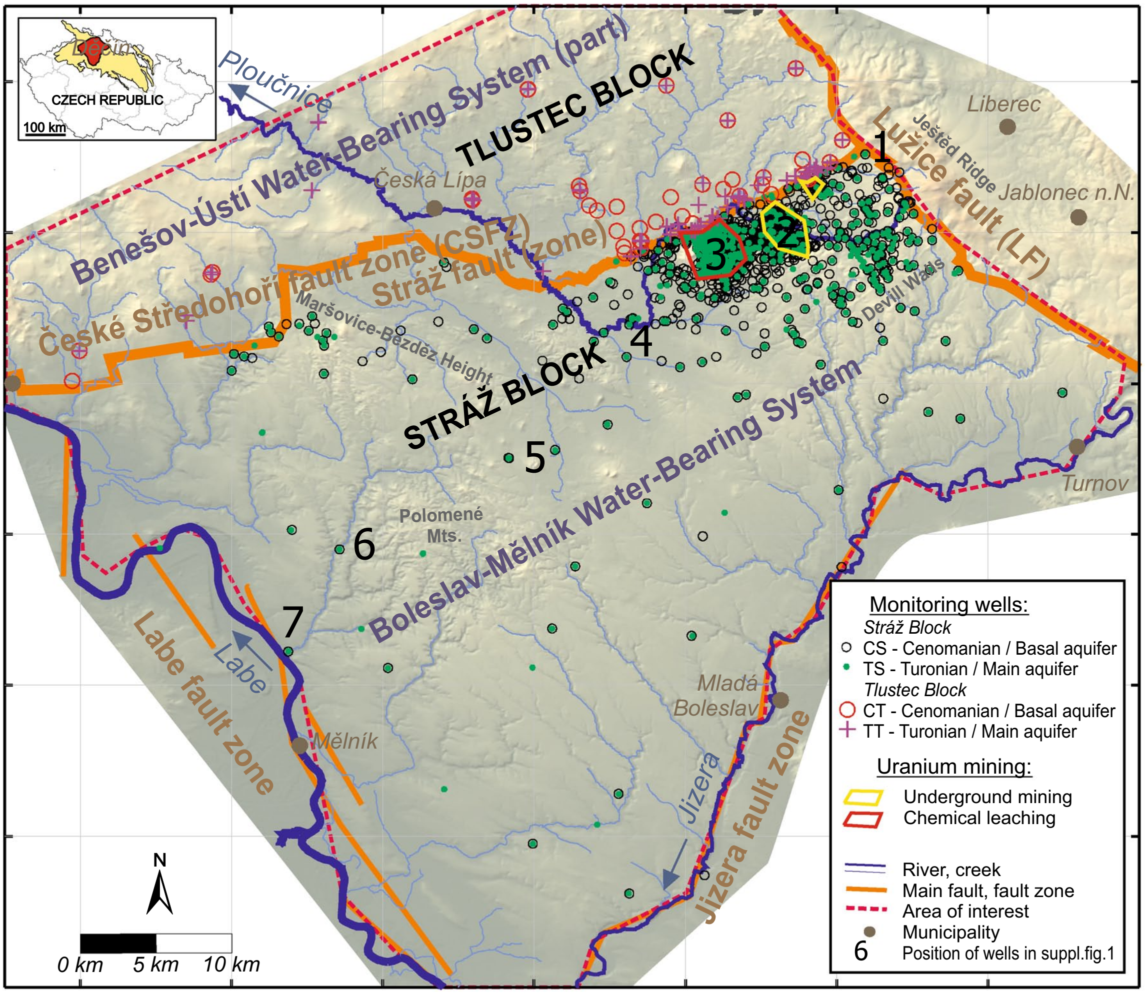

Fig. 1 Map of area of interest showing geologic units, water-bearing systems and main fault zones, mining areas and monitoring wells

2009), and a hydraulic diffusivity that ranges from 5×10^5 to $5\times10^6 m^2\ s^{-1}$ (Krásný et al. 2012); and the Turonian (Main) Aquifer C, in which K ranges from 5×10^{-5} to 1×10^{-4} m s^{-1}, and the effective porosity is 0.15 (Datel 2009). These two aquifers are separated by an aquitard of pellitic sediments of the Bílá Hora Formation and the Jizera Formation (sandy siltstones, siltstones, marlstones, and muddy limestones) with a vertical hydraulic conductivity of 1×10^7 m s^{-1} (Datel 2009). Aquifer D is not present in the Stráž block and is not continuous in the Tlustec block, and therefore is not described in this work.

The Cenomanian aquifer is recharged in a narrow (1–2 km) zone along the LF. Field evidence suggests the presence of parallel faults and rotated blocks of Cretaceous sediments in the footwall block of the LF (Coubal et al. 2014), thus producing a very complicated hydrogeologic structure. Depending on the structural setting of the fault zone, the recharge into the Cenomanian (Basal) aquifer can be direct via the outcrops, or indirect through overlying Turonian sandstones and fractured crystalline rocks shifted over the sandstones on the LF. Further, but limited, recharge is possible through the Turonian aquifer, which overlies the entire area. The Cenomanian aquifer is a confined aquifer, which drains into the Quaternary aquifer and partially to the overlying Turonian aquifer in the Labe River valley.

The Turonian aquifer is recharged mainly by precipitation and partly by leakage from the locally present overlying aquifer D. The Turonian aquifer is mainly unconfined. Confined levels are present only in areas where the overlying aquitard of the Teplice and Březno Formations is present, in part of the Tlustec block. Transmissivity generally decreases towards the SE. The aquifer is drained in the Labe River valley and partly in the Jizera and Ploučnice River basins, where the piezometric level is controlled by drainage to the rivers and their tributaries.

The structural setting plays a subordinate role in groundwater circulation within the main water bodies. The influence of minor faults on groundwater flow direction is mostly insignificant (Kopecký and Slezák 2000; Pačes et al. 2008).

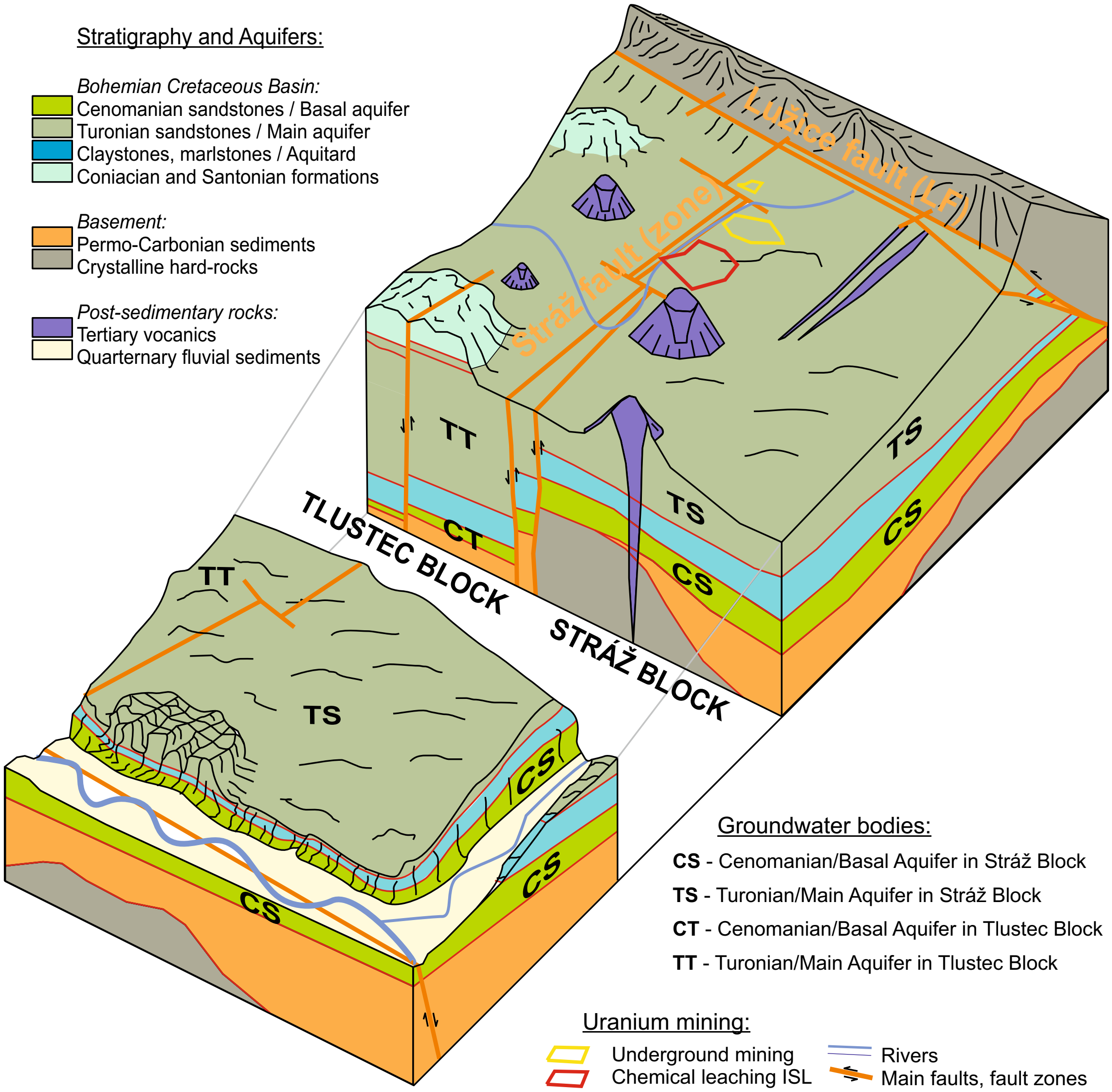

Fig. 2 Generalised geologic settings and groundwater bodies

In general, due to the vertical displacement of aquifers on the Stráž fault zone, there are four groundwater bodies in the area of interest, with individual piezometric behaviour and groundwater flow. These are the: Cenomanian aquifer of the Stráž block (CS), Turonian aquifer of the Stráž block (TS), Cenomanian aquifer of the Tlustec block (CT), and Turonian aquifer of the Tlustec block (TT).

Impact of Important Events on Groundwater

Groundwater in the area of interest has been significantly affected, especially the Cenomanian aquifer of the Stráž block, by the exploration, preparation for, and underground mining of the Hamr pod Ralskem U deposit (MH I, MH II) and the Břevniště deposit (MK I), and the acid ISL on the Stráž pod Ralskem deposit, with the operation of hydraulic barriers and later by the termination of mining and flooding of the underground mines. The important events with respect to the groundwater in the area are outlined in Supplemental Table 1.

Groundwater Monitoring

There are up to 13,000 exploration, monitoring, and in-situ-leaching wells in the area of interest. Since 1965, more than 2100 wells in the described domain have been monitored for changes in water levels (or pressure) by the uranium mining and processing division of DIAMO (a state enterprise) and the Czech Hydrometeorological Institute (CHMI). Piezometric monitoring data are not accessible online.

Water level monitoring wells are irregularly placed in the area of interest (Fig. 1). Most of these wells are placed in the areas of uranium mining, i.e. in the Cenomanian and Turonian aquifer of the Stráž block. Within these two aquifers, most of the monitoring wells are concentrated around the mined areas with a well-to-well distance of several hundreds of meters. In distant areas towards the drainage zone, the well-to-well distance rises to more than 10 km. Some wells are also situated in the Cenomanian and Turonian aquifers of the Tlustec block, where they are aggregated near the Stráž fault. The frequency of monitoring varies in time (daily to biannual values) and space (distant wells are observed less frequently).

The number of wells monitored increased with the exploration and uranium mining from single units in 1965 to 1057 in 2001 (Supplemental Fig. 1). Since 2001, the number of wells where groundwater levels were measured has significantly decreased. Between 2006 and 2007, new monitoring wells were installed within the CHMI network, especially in the SW direction from the mining area towards the drainage zone of the Cenomanian aquifer. Graphs of the piezometric heads observed in the monitoring wells show the long-term groundwater regime in important parts of the Stráž block (Supplemental Fig. 2).

Methods

Over 1.2 million piezometric head observations were sorted into four groups according to groundwater bodies. For each group, a table was created containing the name of the well, X and Y coordinates, and piezometric head elevations above sea level for each year between 1965 and 2014. The piezometric heads were interpolated using Surfer (Golden Software™), using the point kriging method (linear variogram model) with 100 × 100 m grid resolution. Given the widely acknowledged low permeability of the Stráž fault field and vertical displacement of aquifers of about 300 m between the Stráž and Tlustec blocks (Datel 2009; Herčík et al. 2003; Kozáková and Pokorný 2009; Krásný et al. 2012), distinct piezometric head contours were created for the individual groundwater bodies.

The boundaries of the groundwater bodies in the Stráž block were determined by the Stráž and Lužice fault zones and the Jizera and Labe rivers, and in the Tlustec block, by the Stráž and Lužice fault zones, Labe River, and join of Litoměřice and Hrádek nad Nisou municipalities. Contour maps were created from grid files, with contour intervals of 20 m, named according to the groundwater body (CS, TS, CT, TT) and year. Vector maps of groundwater flow direction were created. To delineate areas of potential upward and downward overflow between the Turonian and Cenomanian aquifer, grid files of differences in piezometric heads in individual years were created using the Grid-Math function. The difference in piezometric heads between the Turonian and Cenomanian aquifer was calculated using the following equation:

$$\Delta Z = Z_T - Z_C$$

where ΔZ is the piezometric head difference, Z_T is the piezometric head of the Turonian (main) aquifer, and Z_C is the piezometric head of the Cenomanian (basal) aquifer. Positive values of ΔZ represent an area where the piezometric head of the Turonian aquifer is higher than that of the Cenomanian, resulting in a potential downward overflow, and vice versa. Contour maps of piezometric head difference were created with a contour interval of 20 m. These maps were overlain by a simplified base map, showing the borders of the investigated area, main tectonic zones, watercourses, municipalities, and areas of former underground and ISL mining of U.

The flooding of the mines within the CS aquifer was analysed. When a rising trend in observed piezometric heads was found, an expected time of rebound to the pre-mining levels was calculated from the trend equation.

Results

Development of Piezometric Surfaces in the Stráž Block

Cenomanian Aquifer (Basal Aquifer)—CS

Before mining began, the piezometric head of the Cenomanian aquifer of the Stráž block ranged from approximately 320–340 m above sea level (a.s.l.) at the Lužice fault, to over 270 m a.s.l. in the area of the in-situ leaching fields, down to approximately 170 m a.s.l. towards the Labe River valley drainage area (Fig. 3). During dewatering of the underground area surrounding the Hamr (MH I, MH II) and Křižany (MK I) mines between 1965 and 1990, the CS piezometric surface fell from 300 m a.s.l. to about 130 m a.s.l. (Fig. 4). The resultant depression basin, centred in the Hamr I mine, expanded until around 1991, when its central part stabilized. This area was approximately bordered by the piezometric isoline of 260 m a.s.l. around underground mines. Outside of this line, towards the Lužice fault, the CS piezometric head decline continued until 2002, and in some parts of the area (close to the Stráž and Lužice faults), it still continues to decline.

In contrast, in the chemical leaching area (the Stráž deposit), the CS head rose by up to 30 m between 1970 and 1990 to 310 m a.s.l., reaching the line of hydraulic barriers (HB Stráž and HB Svébořice, in full operation since 1985). From 1990 to 2001, the groundwater regime in the CS aquifer in the area around the Hamr mine was relatively stable. An extreme hydraulic gradient was established between the underground mining area and the ISL site. The difference in piezometric levels between the Stráž HB and drainage crosscuts of the Hamr mine was up to 170 m over a distance of 2.2 km. Towards the LF, a slow decline of piezometric levels continues, but to the southeast and south of the Hamr mine, the decline was significant (up to 40 m). In the area of the ISL fields, the CS head declined by up to 50 m compared to 1990 (to 250–270 m a.s.l.). The reach of the decreased levels extends significantly towards the SW.

After 1990, the Křižany mine area became flooded. By 2000, the CS piezometric head around the Křižany mine had increased by 20–30 m, to about 240 m a.s.l. (Fig. 5).

In 2003, pumping of water from the Hamr mine was terminated. The total volume of mine water pumped out of MH during the period 1966–2003 was 435.5 million m^3. To increase the flooding rate, alkalised water from sludge lagoons was pumped into the MH area. In total, 4.7 million m^3 (Datel 2009; Ekert and Mužák 2010) of water was pumped into the mine.

Since 2001, there has been a significant rise of CS piezometric heads in the central part of the cone of depression. By the end of 2003, the groundwater level reached the ceiling of the Cenomanian aquifer, rising up to 25 m $year^{-1}$. Subsequently, the rate of piezometric head rise significantly decreased to 5–6 m $year^{-1}$ in the central part of the cone of depression.

The rate of flooding varies over the area of interest. To the south, the CS piezometric head rises over an area of tens of kilometres; however, near the Lužice fault, a slow gradual decline in CS heads still continues. In the ISL area, the CS piezometric head has gradually declined since 1990, from about 300 to 225 m a.s.l. in 2014, as part of the remediation process instituted to prevent acidic solutions from spreading into the overlying Turonian aquifer. At the end of 2014 (Fig. 6), the CS piezometric head reached a maximum of 320 m a.s.l. near the LF. An asymmetrical depression in CS head (240 m a.s.l.) near the Stráž fault is still visible north of the MH in the mined area.

There has been an ascending linear trend in piezometric levels during the past 10 years since a confined groundwater regime had been reached. Based on this trend, the earliest return to pre-mining piezometric head is estimated to occur around 2025 in the MH area (Supplemental Fig. 3). In the MH area, the cone of depression is now decreasing while in the MK area, the rise of water level has almost stopped. In the northernmost part of the Stráž block near the contact of the Stráž fault and LF, a slow decrease (<1 m per year) of Cenomanian aquifer heads still continues.

The significant hydraulic gradient between the MH area and the ISL fields disappeared around 2010 due to flooding of the underground mines, but also due to noticeable lowering of the CS piezometric head in the ISL area associated with remediation. Currently, the ISL area represents a new depression within the Cenomanian aquifer with a minimum of 225 m a.s.l. separated by the linear Stráž hydraulic barrier from piezometric depression in the MH area. Piezometric head monitoring in the ISL area and its southwestern forefield shows a slowly rising trend since 2003. The earliest expected return to pre-mining piezometric head levels in the ISL area is around 2045 (Supplemental Fig. 4).

Turonian Aquifer (Main Aquifer)—TS

Before mining, the piezometric surface of the Turonian aquifer in the Stráž block was up to 450–470 m a.s.l. at the LF and declined towards the Labe River valley to about 170 m a.s.l. (Fig. 3), with a minor depression in the Ploučnice River valley (260 m a.s.l.) and elevations in the Polomené Mountains and Maršovice–Bezděz Height (up to 330 m a.s.l.). The groundwater regime in the Turonian aquifer in a narrower area of the Stráž block was relatively stable during mining and closure of the underground mines. This stability was only affected by the breakthrough into the MH I mining chamber in May 1984, which created a short-term connection between the Cenomanian and Turonian aquifers and caused a significant decline in the TS head near the MH I. In the ISL area, the TS piezometric heads have been significantly lowered since 1992 due to pumping of residual acidic solutions from the Cenomanian aquifer (Fig. 5), and the so-called lenses of contaminated Turonian groundwater.

Groundwater: A Broader Perspective

Stráž Block

In the Stráž block, significant fluctuations of the CS piezometric surface while intensive mining was taking place had almost no effect on the Turonian piezometric surface. However, the increasing difference between the piezometric head of the Cenomanian and Turonian aquifers in the southwestern forefield of the ISL site led to considerable areal expansion of potential upward leakage and local spreading of contaminated water from the Cenomanian to the Turonian aquifer. Contaminated water flowed through the numerous exploration and production wells, as well as through natural faults and fractures, and created “lenses” of spatially limited contamination of the TS aquifer (Datel 2009; Ekert and Mužák 2010; Krásný et al. 2012). Piezometric depression in the CS extended to the central part of the Stráž block until the year 2000. Further extension towards the south and southwest followed the pumping change at the ISL site after remediation began.

Since flooding of the underground mining areas was initiated in April 2001, through 2014, the piezometric surface

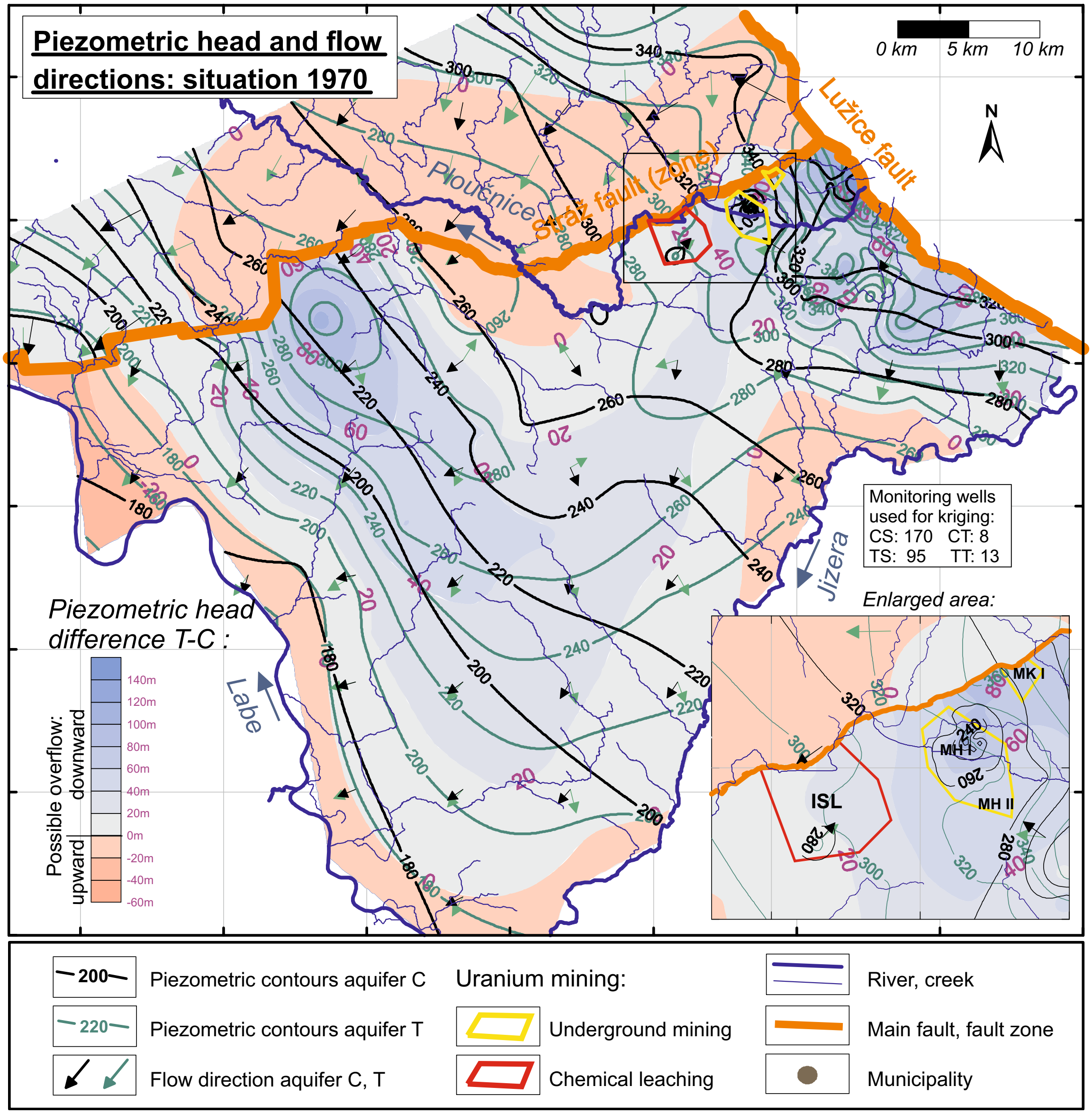

Fig. 3 Piezometric head and flow directions: situation 1970—initial period of mining

of the Cenomanian aquifer has risen by 100–120 m in the central part of the Stráž block (Figs. 5, 6). In the wider area of the Stráž block—northeast towards the LF and southwest from the ISL site—a slow gradual decline of piezometric heads of the Cenomanian aquifer still continues, as does the decrease in piezometric head of both aquifers in the Stráž block, towards their drainage area in the Labe River valley.

The piezometric surface of the Cenomanian aquifer is currently significantly lower in the entire Stráž block area than when mining started. In the area of residual piezometric depression around the former underground mines, the difference in CS heads is approximately 50–60 m, while it is 20–30 m near the LF, 60–70 m in the ISL area, and 20–30 m in the area south and southwest of the ISL.

Tlustec Block

Groundwater in the Tlustec block in both the Cenomanian and Turonian aquifers has been relatively stable during the entire observed period, reflecting only climatic oscillations, with a tendency of smoothing in the direction from the LF towards the drainage area in the Labe river valley. The CT piezometric surface falls gradually from ≈340 m a.s.l. at the LF to 190 m a.s.l. in the Labe River valley, whilst the TT piezometric surface falls from 360 m a.s.l. to 160 m a.s.l.

Almost no influence on piezometric head was detected across the Stráž fault zone and its southwest elongation. Only in a short section near the Křižany mine did the TT piezometric head respond to the significant lowering of the CS piezometric head: the piezometric heads changed from a slightly

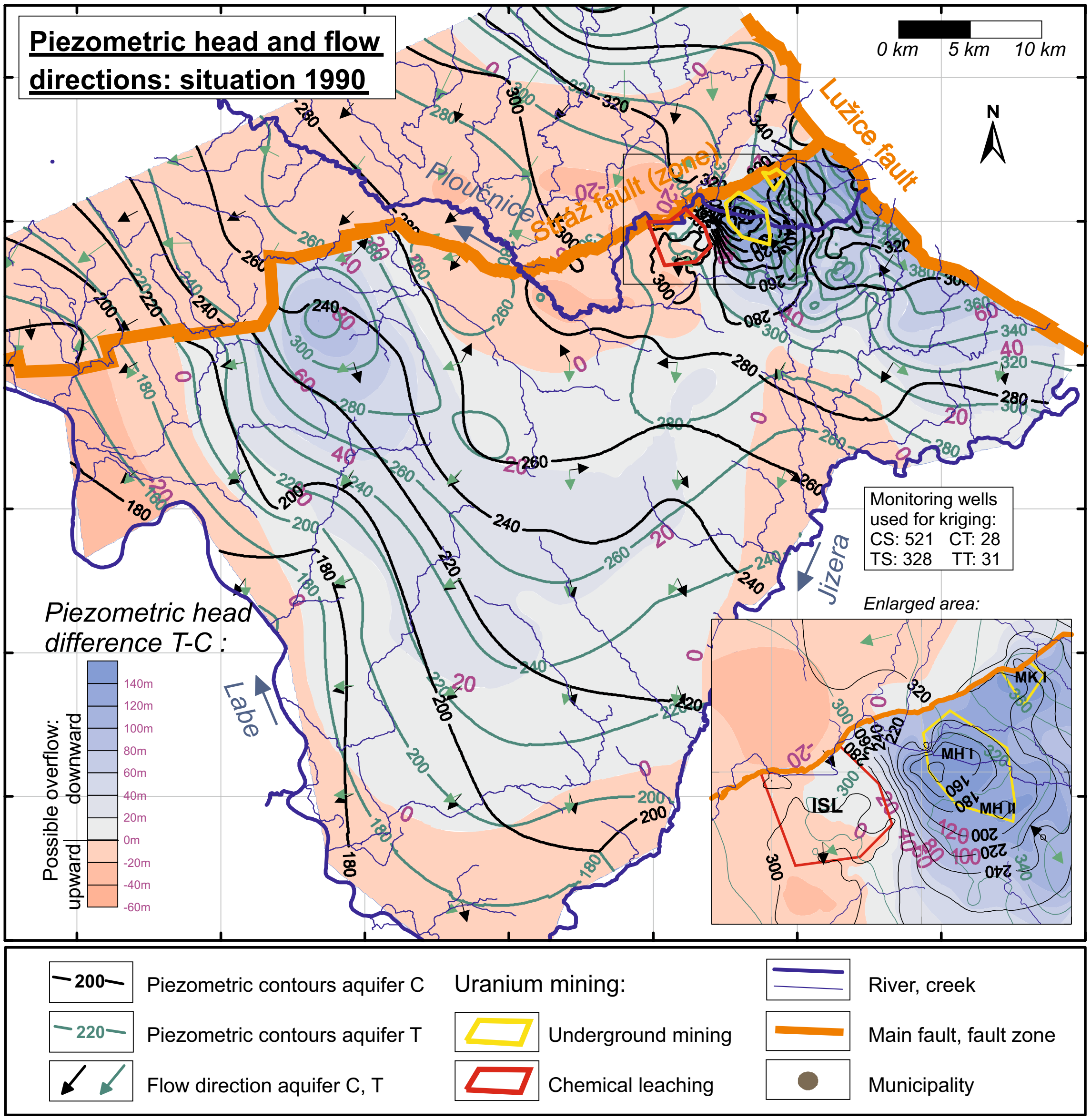

Fig. 4 Piezometric head and flow directions: situation 1990—maximum affect period

downward to a slightly upward trend in response to the dewatering and subsequent flooding of the underground mine in the MK I area. The CS piezometric head oscillation (≈40 m) caused the TS and TT piezometric heads to fluctuate, but only over a range of a few meters to fractions of a metre.

Discussion

Areas of potential vertical upward flow of groundwater and possible overflow from the Cenomanian to Turonian aquifer have been identified in the Stráž block by comparing the difference in piezometric surfaces between the aquifers. During the initial period of mining, in 1970, an area of a potential overflow from the Cenomanian to the Turonian aquifer occurred near the Ploučnice River (Fig. 3). The difference in heads was small, up to 10 m. A second area where Cenomanian piezometric surface was higher than the Turonian was where both aquifers drain in the Labe River valley.

As mining intensified, the area of potential overflow from the Cenomanian to Turonian aquifer was significantly extended (Fig. 4). This situation was caused by a significant increase of the Cenomanian piezometric head due to injection of leaching solutions into the Cenomanian aquifer near the ISL area, and the operation of hydraulic barriers. In the southwestern forefield of the ISL, the piezometric surface of the Cenomanian aquifer was more than 20 m higher than the Turonian aquifer. Another area of potential overflow from the Cenomanian to Turonian aquifer appears to be the headwater area of some right-hand tributaries of the Jizera River.

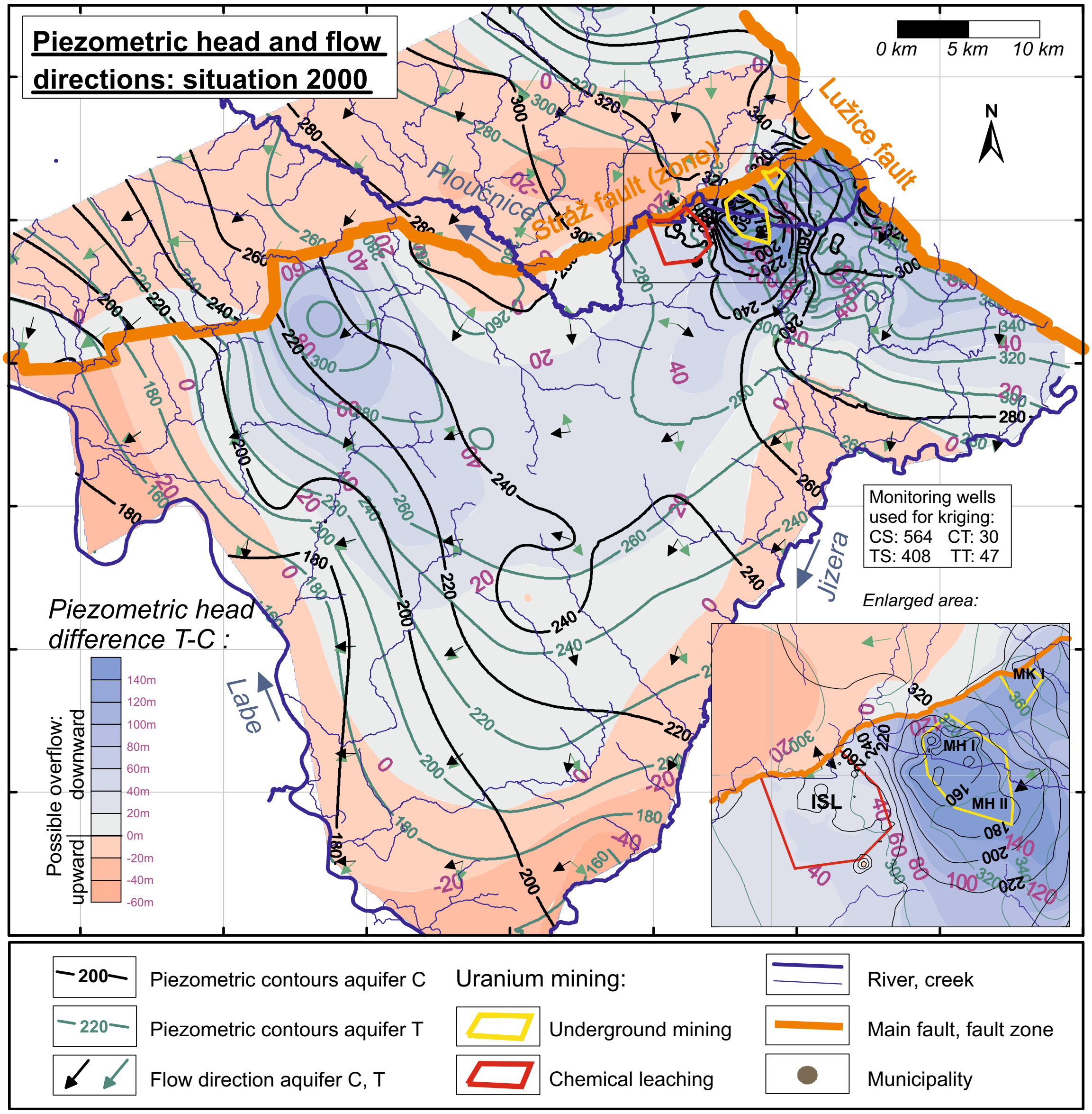

Fig. 5 Piezometric head and flow directions: situation 2000—flooding of underground mines

After 1996, when the piezometric head in the Cenomanian aquifer in the ISL area was lowered by 50–70 m by the remediation effort, the area of potential overflow from the Cenomanian to Turonian aquifer was significantly reduced (Fig. 5), the CS piezometric surface in the southern forefield of the ISL area declined (due to continued expansion of the Cenomanian cone of depression), the potential overflow of the upper reaches of the right-hand tributaries of the Jizera River began to disappear. This lowering of the CS piezometric surface in the ISL area (remediation pumping) still continues, further increasing the differences in levels, and favouring potential downward flow from the Turonian into the Cenomanian aquifer. This eliminates the potential risk of contamination to the Turonian aquifer. At present, the piezometric heads in the Cenomanian aquifer are higher than in Turonian aquifer only on the southern and south-western edge of the investigated area, toward the Labe River valley (Fig. 6).

Two general patterns of long-term piezometric head evolution can be found in the Stráž block, with a tendency of smoothing and retardation from the centre to the margins:

(1) “underground mining pattern” (Supplemental Fig. 3) in the NE part of the Stráž block, approximately to a line connecting the hydraulic barrier near MH towards the town of Mladá Boleslav,
(2) “ISL pattern” (Supplemental Fig. 4) in the ISL site and its S and SW forefield towards the Labe River valley.

No such patterns are obvious in the other aquifers. Therefore, it can be assumed that observed changes in the CS groundwater regime were caused by mining in the Stráž

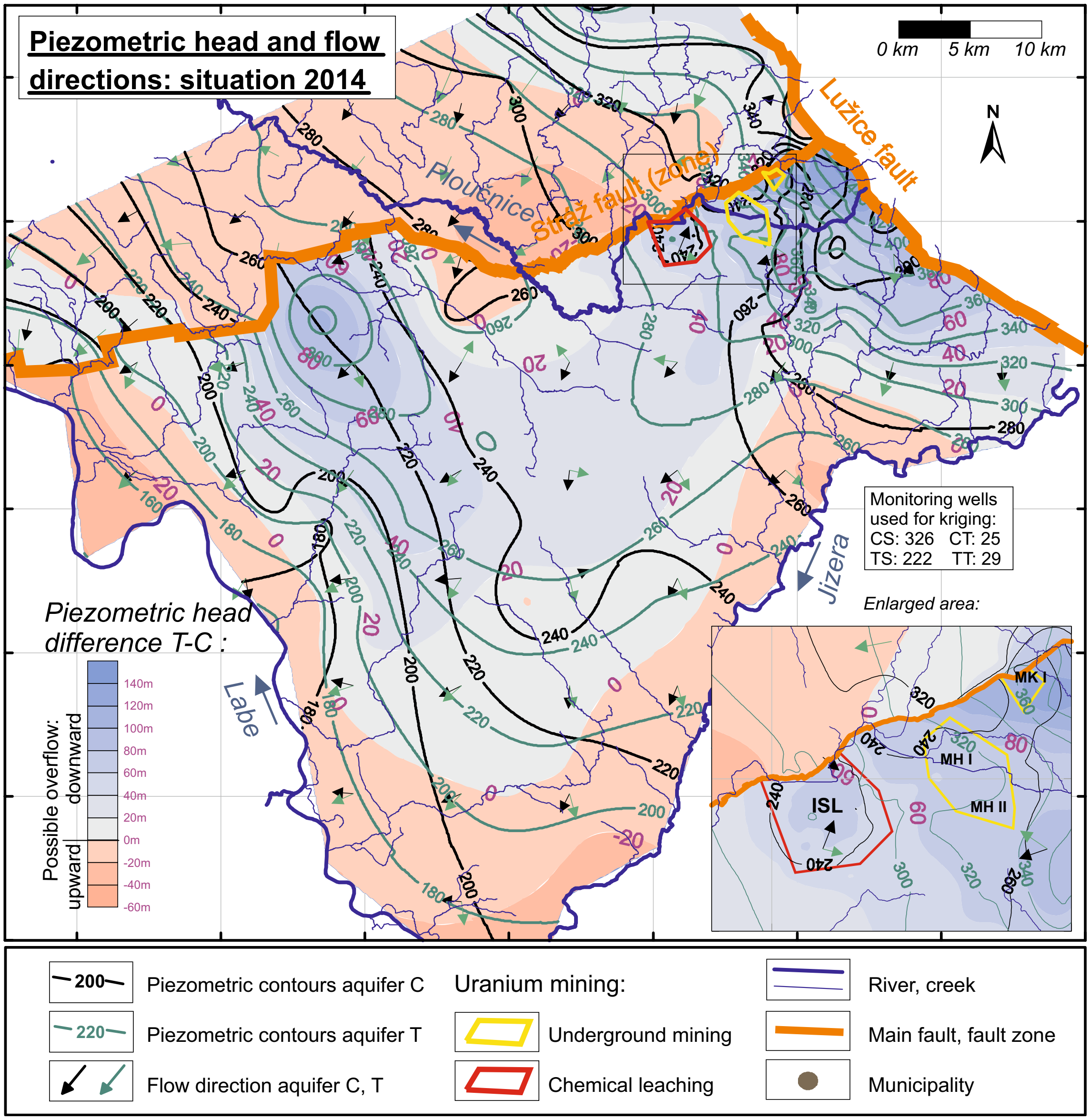

Fig. 6 Piezometric head and flow directions: situation 2014—present state

block, even in the case of wells that have only been monitored for a short time.

If we compare the piezometric surface of the Cenomanian aquifer from the beginning of underground mining to the present, it is obvious that the piezometric surface of the Stráž block is now significantly lower. At the current rate of flooding, we can presume that the piezometric surface in the mined areas will reach pre-mining conditions around the year 2025 at the earliest. Even though a linear trend has been observed since the CS aquifer returned to the confined regime, the piezometric head rise is expected to slow. Based on the continuing slow decline in CS piezometric heads near the LF, we can presume that the piezometric surface will reach pre-mining conditions within several decades, at the earliest. The possibility of returning to the natural groundwater regime in the ISL area and its southern and southeastern forefield depends on the continued use of remediation technology. Overall, more than 100 years are likely to elapse from the launch of preparations for underground U mining until the restoration of the natural hydrogeological regime. However, one positive fact has been revealed: that such extensive intervention into an aquifer in a multi-layered groundwater system did not affect the other aquifers in the area of interest, especially the Turonian aquifer, which is widely used for water supply.

The question that remains is whether there will be any observable impact of the large number of boreholes drilled through the aquitard into the Cenomanian aquifer after the piezometric head returns to its natural state. Especially in the southwestern forefield of ISL site, conditions for potential upward overflow from the Cenomanian to Turonian aquifer may arise. Damaged or improperly sealed wells could further spread acidic leachates into the overlying Turonian aquifer, even after a temporarily successful remediation.

Conclusion

The natural groundwater flow regime in the Cenomanian aquifer of the Stráž block (basal aquifer A in the Boleslav–Mělnik water-bearing system) was heavily influenced by the mining of radioactive material near the Stráž pod Ralskem, in the Czech Republic. This was the largest intervention into the groundwater flow regime in the territory of the Bohemian Cretaceous Basin in history, extending more than 50 km along the regional flow direction. The piezometric surface of the basal Cretaceous aquifer was affected over a much larger area (600–700 km^2) than the area impacted by the in situ leaching, estimated between 24 (Lusk 1998; Slezák 2001) and 27 km^2 (Datel 2009; Ekert and Mužák 2010; Vokál et al. 2013).

This extensive intervention into the groundwater regime of the basal Cretaceous aquifer must be seen in the context of its long-term development, especially when evaluating current groundwater levels in monitoring wells and their long-term characteristics. The observed upward trend in groundwater levels in monitoring boreholes reflects only partial restoration of aquifer conditions to the natural state that existed prior to mining.

Due to irregular placement of the monitoring wells within the area of interest (near the mines, the wells are hundreds of meters apart, whereas at the limits of the surveyed area, the wells are up to 20 km apart), the constructed maps of piezometric surfaces reflect detailed groundwater conditions near the former mine sites, but a rather generalized regional image in the wider area, with suppressed local influence. Still, the compiled maps of piezometric surfaces of individual aquifers in the area allow one to develop an understanding of the long-term trends in changes in groundwater heads and flow directions. Unlike previously published works (Herčík et al. 2003; Krásný et al. 2012), where piezometric contours were presented as static, the newly created maps provide insight into the dynamics of the Bohemian Cretaceous Basin water-bearing system, even though this study does not present a hydraulic model, but an interpolation of monitoring data. The piezometric surfaces can be used to calibrate hydraulic models in the area of interest.

Based on the far-reaching influence of mine drainage and flooding on the piezometric surface of the Cenomanian aquifer towards the southwest, i.e. in the natural direction of groundwater flow, it is appropriate to refer to the entire area of the Boleslav–Mělník water-bearing system adjacent to Středohoří Fault Zone (from the infiltration area at LF to the drainage area in the Labe River valley) as the Stráž block in the wider sense.

Acknowledgments The author thanks the Division of Uranium Mining and Processing (TÚU) of DIAMO (a state enterprise) and the Czech Hydrometeorological Institute (CHMI) for providing groundwater monitoring data. The work was partly conducted as part of the project "Quantification of the Overflow Between the Cenomanian and Turonian Aquifer" (Datel 2009) and its subsection "Groundwater Monitoring—Analysis of Conditions, Proposal of Optimisation" (Lipanský 2009) and updated to the situation at the end of 2014.

References

Adams R, Younger PL (2001) A strategy for modeling ground water rebound in abandoned deep mine systems. Ground Water 39(2):249–261

Balatka M, Čermáková H, Novák J, Mužák J (2006) The optimal strategy of cleaning of fucoid sandstone. In: Merkel B, Hasche-Berger A (eds) Uranium in the environment. Springer, Berlin, pp 437–447. doi:10.1007/3-540-28367-6_43

Cajz V, Adamovič J, Rapprich V, Valigurský L (2004) Newly identified faults inside the volcanic complex of the České Středohoří Mts, Ohře/Eger Graben, North Bohemia. Acta Geodyn Geomater 1(2): pp 213–222

Čermáková H (2002) Optimizing the remediation of the subsurface environment in the Stráž deposit. In: Uranium in the aquatic environment. Springer, Berlin Heidelberg, pp 793–802

Coubal M, Adamovič J, Málek J, Prouza V (2014) Architecture of thrust faults with alongstrike variations in fault-plane dip: anatomy of the Lusatian Fault, Bohemian Massif. J Geosci 59:183–208. doi:10.3190/jgeosci.174

Datel JV (2009) Kvantifikace přetoku mezi cenomanským a turonským kolektorem. Závěrečná zpráva o provedených pracech v období 2007–2009. Stráž pod Ralskem, Quantification of the overflow between the Cenomanian and Turonian Aquifer—final report (**in Czech**)

Datel JV, Ekert V (2008) Environmental impacts of mine waters from chemical and deep uranium mining—Straz pod Ralskem, Czech Republic In: Rapantova N, Hrkal Z (eds), Proceedings of the 10th international mine water assoc (IMWA) congress, Karlovy Vary, Czech Republic, pp 197–200

Ekert V (2008) Environmental impact of mine water from chemical extraction and underground uranium mining—Straz pod Ralskem, Czech Republic. In: Rapantova N, Hrkal Z (eds) Proceedings of the 10th IMWA Congress 2–5 June, 2008 Karlovy Vary, Czech Republic, pp 197–200

Ekert V, Mužák J (2010) Mining and remediation at the Stráž pod Ralskem uranium deposit. Geosci Eng 56(3):1–6

Golden Software (2002) Surfer 8. Contouring and 3D surface mapping for scientists and engineers. User's guide. Golden Software, Inc, Golden

Herčík F, Kůrka J (1990) Indication of contaminated ground water in the vicinity of settling pond of uranium ore treatment plant at Straz pod Ralskem. Geologicky Pruzkum 32(7):197–200. https://inis.iaea.org/search/search.aspx?orig_q=RN:22059728

Herčík F, Valečka J, Herrmann Z (2003) Hydrogeology of the Bohemian Cretaceous Basin, 1st edn. Czech Geological Survey, Prague

Hokr M, Maryška J, Severýn O (2004) Application of numerical model on extraction of underground contamination: identification of dual-porosity properties. In: Proceedings of the 13th international soil conservation organization conference, https://www.researchgate.net/publication/260319215

IAEA (1993) Uranium in situ leaching. IAEA, Vienna, IAEA-TECDOC-720
IAEA (2005a) Guidebook on environmental impact assessment for in situ leach mining projects. IAEA, Vienna
IAEA (2005b) The Straz block ISL project, app. VII, guidebook on environmental impact assessment for in situ leach mining projects. IAEA, Vienna, pp 119–131
Jakubick A, Jenk U, Kahnt R (2002) Modelling of mine flooding and consequences in the mine hydrogeological environment: flooding of the Koenigstein mine, Germany. Environ Geol 42(2–3):222–234
Jenk U, Frenzel M, Metschies M, Paul M (2014) Flooding of the underground uranium leach operation at Königstein (Germany)—a multidisciplinary report. In: Proceedings of the IMWA annual congress
Kafka J (ed) (2003) Rudné a uranové hornictví České republiky. Ostrava: Anagram. Ore and Uranium Mining in the Czech Republic (**in Czech**)
Klinger C, Jenk U, Schreyer J (2000) Investigation of efficacy of reactive materials for reduction of pollutants in acid mine water in the former uranium mine of Königstein (Germany). In: Proceedings of the 7th IMWA congress, Katowice-Ustron, Poland, pp 11–15
Kopecký P, Slezák J (2000) Uranium mining in the North Bohemia, Straz, Czech Republic and geological evaluation prior to remediation. In: The uranium production cycle and the environment, vol 2. IAEA, Vienna, pp 380–385
Kozáková V, Pokorný R (2009) Tektonické poruchy a potenciálníi rizika mezikolektorové kontaminace podzemních vod ve strážskem bloku. Zprávy o geologických výzkumech, Česká geologická služba, Tectonics and potential risk of inter-aquifer contamination of groundwater in the Stráž Block, Praha, pp 248–251 (**in Czech**)
Krásný J, Císlerová M, Čurda S, Datel JV, Dvořák M, Grmela A, Hrkal Z, Kříž H, Marszalek H, Šantrůček J, Šilar J (2012) Podzemní vody České republiky: regionální hydrogeologie prostých a minerálních vod. Vyd. 1. Praha: Česká geologická služba, Groundwater of the Czech Republic: Regional hydrogeology of fresh and mineral water (**in Czech**)
Lietava P (2000) Risk-assessment model for evaluating environmental remediation options at the Stráž underground uranium leaching site. In: The environmental challenges of nuclear disarmament, Springer, Dordrecht, pp 191–204
Lipanský T (2009) Závěrečná zpráva úkolu „Kvantifikace přetoku mezi cenomanským a turonským kolektorem“, kniha IB Monitoring podzemních vod, analýza stavu, návrh optimalizace. Stráž pod Ralskem. Final report Quantification of Overflow between the Cenomanian and Turonian Aquifer, book IB, Groundwater monitoring, analysis and proposals (**in Czech**)
Lusk K (1998) Monitoring podzemních vod v severočeské oblasti těžby uranových rud, Sbor 10. hydrogeol konfer, Stráž pod Ralskem. Groundwater Monitoring in North-Bohemian Uranium Mining Area, pp 82–86 (**in Czech**)
Merkel B (2002) Flooding of the Königstein uranium mine—aquifer reactivity versus dilution. Uranium in the aquatic environment. Springer, Berlin, pp 263–272. doi:10.1007/978-3-642-55668-5_30
Merkel B, Planer-Friedrich B, Wolkersdorfer Ch (eds) (2002) Uranium in the aquatic environment. In: Proceedings of the international conference on uranium mining and hydrogeology III and the IMWA symposium, Freiberg, Germany. Springer, Berlin Heidelberg
Mužák J (2008) Remediation of consequences of chemical leaching of uranium in Straz pod Ralskem. In: Rapantova N, Hrkal Z (eds) Proceedings of the 10th IMWA congress, Karlovy Vary, Czech Republic, pp 217–220
Novák J (2001) Groundwater remediation in the Stráž leaching operation. Mine Water Environ 20:158–169
Novák J, Mužák J (2002) Flooding of the deep uranium mine Hamr I by free water from tailings pond. In: Merkel B, Planer-Friedrich B, Wolkersdorfer C (eds) Proceedings of the international conference on uranium mining and hydrogeology III and the IMWA Symposiu, Springer, Berlin Heidelberg, pp 311–318
Novák J, Mužák J, Smetana R, Wasserbauer V (2000) Numerical modelling of ISL process in Straz uranium deposit. Uranium Prod Cycle Environ 2:527–529
Novák J, Mužák J, Smetana R (2002) Control of remediation of uranium deposit Stráž with use of numerical modelling approach. Uranium Prod Cycle Environ 2:524–526
Pačes T, Alvarado JC, Herrmann Z, Kodeš V, Mužák J, Novák J, Purtschert R, Remenárová D, Valečka J (2008) The Cenomanian and Turonian aquifers of the Bohemian Cretaceous Basin, Czech Republic. In: Edmunds WM, Shand P (eds) Natural groundwater quality. Blackwell Publ, Malden, Chap 17, pp 372–390
Paul M, Jenk U, Meyer J, Gengnagel M (2006) Source manipulation in water bodies of flooded underground mines–experiences from the Wismut remediation program. In: Proceedings of the 7th ICARD, pp 26–30
Paul M, Meyer J, Jenk U, Baacke D, Schramm A, Metsches T (2013) Mine flooding and water management at underground uranium mines two decades after decommissioning. In: Proceedings of the IMWA conference, pp 1081–1087
Robertson AJ, Ranalli AJ, Austin SA, Lawlis BR (2016) The source of groundwater and solutes to Many Devils Wash at a former uranium mill site in Shiprock, New Mexico. USGS Scientific Investigations Report 2016–5031, Reston
Skácelová Z, Mlčoch B, Tasáryová Z (2011) Digital model of the crystalline basement and Permo-Carboniferous volcano-sedimentary strata in the Mnichovo Hradiště Basin and Correlation with the geophysical fields (Czech Republic). Acta Geodyn Geomater 8(3):225–235
Slezák J (2001) Historie těžby uranu v oblasti Stráže pod Ralskem v severočeské křídě a hydrogeologie - Sbor geol Věd, Hydrogeol., inž Geol Ústř. Úst geol, Praha, The history of uranium mining in Stráž pod Ralskem nad Hydrogeology, Bohemian Cretaceous Basin, pp 5–36 (**in Czech**)
Smetana R, Mužák J, Novák J (2002) Environmental Impact of uranium ISL in Northern Bohemia. In: Merkel B, Planer-Friedrich B, Wolkersdorfer Ch (eds) Proceedings of the international confernce on uranium mining and hydrogeology III and the IMWA symposium, Springer, Berlin Heidelberg, pp 699–708
Taylor G, Farrington V, Woods P, Ring R, Molloy R (2004) Review of environmental impacts of the acid in-situ leach uranium mining process. CSIRO Land and Water Client Report, CSIRO, Clayton
Uličný D (2001) Depositional systems and sequence stratigraphy of coarse-grained deltas in a shallow-marine, strike-slip setting: the Bohemian Cretaceous Basin, Czech Republic. Sedimentology 48:599–628
Uličný D, Laurin J (2001) Well-log—based correlation of Turonian—Lower Coniacian depositional systems in the western part of the Bohemian Cretaceous Basin: new Basis for reconstructing the basin history. Abstr, 6th Meeting of the Czech Tectonic Studies Group, Donovaly, Geolines 13: 121
Uličný D, Špičáková L, Grygar R, Svobodová M, Čech S, Laurin J (2009a) Palaeodrainage systems at the basal unconformity of the Bohemian Cretaceous Basin: roles of inherited fault systems and basement lithology during the onset of basin filling. Bull Geosci 84(4):577–610
Uličný D, Laurin J, Čech S (2009b) Controls on clastic sequence geometries in a shallow-marine, transtensional basin: the Bohemian Cretaceous Basin, Czech Republic. Sedimentology 56:1077–1114. doi:10.1111/j.1365-3091.2008.01021.x
Valečka J (2009) Proboštov Fault Field, the newly identified tectonic structure in the eastern partof the České středohoří Mts. Zprávy o

geologických výzkumech v roce 2008. Česká geologická služba, Praha (**in Czech**)

Vokál V, Mužák J, Ekert V (2013) Remediation of Uranium In-Situ Leaching Area at Stráž pod Ralskem, Czech Republic. In: Proceedings of the 15th international conference on environmental remediation and radioactive waste management, American Society of Mechanical Engineers, pp V002T04A016–V002T04A016

Wolkersdorfer Ch, Bowell R (eds) (2005) Contemporary reviews of mine water studies in Europe, part 3. Mine Water Environ 24:58–76

Zielinski RA, Chafin DT, Banta ER, Szabo BJ (2007) Use of 234U and 238U isotopes to evaluate contamination of near-surface groundwater with uranium-mill effluent: a case study in south-central Colorado, USA. Environ Geol 32(2):124–136