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Anthropogenic impact on the groundwaters between Bohemian Massif and Western Carpathians

Habilitation thesis

TOMÁŠ KUCHOVSKÝ

Department of Geological Sciences

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Author: Tomáš Kuchovský
Faculty of Science
Masaryk University
Department of Geological Sciences

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Abstract

The impact of anthropogenic activities on groundwaters is examined in three topics representing the current issues in industrialized countries worldwide: the influence of raw materials extraction, groundwater contamination, and the geothermal energy extraction. Theoretical methodological approaches were applied to site-specific conditions, creating specific methodology for given site to obtain data set for subsequent 3-D groundwater flow modelling. The significant impact of mining on groundwaters (changes in hydraulic heads) and surface streams (decrease in discharges and desiccation) were identified in the Rosice-Oslavany black coal mining district and the Mohelnice-Moravičany open pit, but rather in local extent. 3-D modelling of groundwater flow enabled precise quantification of changes in the water balance and, in the case of deep mining, also the changes in the hydraulic parameters of rocks affected by mining. Long-term abandoned flooded underground mine workings show a stabilized state, which, even with the observed impacts on water features in the landscape, must be understood as newly established non-reversible natural conditions. On the contrary, gravel mining can significantly affect the sustainable capacity of important water sources. Given the progression of gravel open pit mining and predicted climate change according to climate scenarios accepted by the scientific community, the reduction of groundwater resources may pose a serious risk, as demonstrated on the Čeperka site supplying drinking water for 100.000 inhabitants.

In the case study of groundwater contamination with chlorinated solvents at three case study sites, it has been demonstrated that under suitable reduction conditions in aquifers, high concentrations of contaminants can be significantly reduced, depending on the site-specific terminal electron accepting process. Even in the cases of concentrations close to the solubility limits, monitored natural attenuation as a remediation method can be successful.

The limits of geothermal energy extraction are always dependent on natural conditions in aquifers. The geothermal potential of the Jurassic aquifer near Pasohlávky containing thermal water has been studied using 3-D modelling involving density dependent flow, evaluation of hydrochemistry and geothermometers, determination of the maximum temperatures and the depth of thermal water circulation. The inflow of fresh meteoric water has been identified in the NW aquifer section, while higher mineralization and temperatures connected with the presence of marinogenic waters were identified in the SE section. Potential risks of degradation of this promising structure arise from future excessive use of water, which may also threaten the current balneological use.

Declaration

I declare that I have prepared my thesis independently using the information sources provided in the thesis.

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[P1] VANICEK, Petr, Adam RICKA, Tomas **KUCHOVSKY**, Bibiana PASTERNAKOVA, Katerina CHROUSTOVA a Karel SUHAJDA. Sustainable groundwater resource extraction influenced by changing climate and pit lake expansion in East Bohemia, Czech Republic. *Journal Of Hydrology-Regional Studies* [online]. 2025, **59**(102400, Article 102400). ISSN 2214-5818. doi:10.1016/j.ejrh.2025.102400

[P2] **KUCHOVSKY**, Tomas, Adam ŘÍČKA a Jaroslava ČERVENKOVÁ.Impact of Gravel Pits on Ground water: Case study of Gravel Pits near the Mohelnice City, Czech Republic. In Mine Water and the Environment PROCEEDINGS, 10th International Mine Water Association Congress, June 2-5. 2008, Karlovy Vary, Czech Republic. Ostrava: VŠB - Technical University of Ostrava. 2008, 69 - 72, ISBN 978-80-248-1767-5.

[P3] **KUCHOVSKY**, Tomas, David GRYCZ a Michala DRÁBOVÁ. Regional Impact of Mining on Stream Drainage Characteristics in the Rosice - Oslavany Coal Mining District, Czech Republic. In Mine Water and the Environment PROCEEDINGS, 10th International Mine Water Association Congress, June 2-5. 2008, Karlovy Vary, Czech Republic. Ostrava: VŠB - Technical University of Ostrava. 2008, 155 - 158, ISBN 978-80-248-1767-5.

[P4] RICKA, Adam, Tomas **KUCHOVSKY**, Ondra SRACEK a Josef ZEMAN. Determination of potential mine water discharge zones in crystalline rocks at Rozna, Czech Republic. *Environmental Earth Sciences* [online]. 2010, **60**(6), 1201–1213. ISSN 1866-6299. doi:10.1007/s12665-009-0261-8

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[P7] CHROUSTOVA, Katerina, Adam RICKA, Bibiana PASTERNAKOVA, Tomas **KUCHOVSKY**, Thomas R. RUDE a Josef ZEMAN. Identification of deep Czech Republic-Austria transboundary aquifer discharge and associated river chloride loading. Environmental Earth Sciences [online]. 2024, 83(12, Article 366). ISSN 1866-6299. doi:10.1007/s12665-024-11670-7

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1 Introduction

The habilitation thesis summarizes the main results of the candidate's research in the period after obtaining his Ph.D. The candidate's professional specialization is hydrogeology; the field of the habilitation procedure at the Faculty of Science is Geology.

One of the 17 Sustainable Development Goals (SDGs) defined by the United Nations is to ensure availability and sustainable management of water and sanitation for all (Goal 6). Water, as one of the essential substances for humans, requires adequate protection of the quantity and quality of water resources that are important for supplying the population. Groundwater, as the world's second largest reservoir of fresh water, is essential for the sustainable development of human society.
The geological environment at the boundary between the Bohemian Massif and the Western Carpathians is characterized by a variety of rock formations, including crystalline rocks, basin structures, and platform sediments. The specific geological development of this area has resulted in the presence of all basic types of aquifers with typical characteristics of groundwater formation, circulation, and drainage within a relatively small area. Thanks to favourable geological, geomorphological, and climatic conditions, significant groundwater resources are formed, and their concentrated withdrawals make it possible to supply smaller municipalities and large cities. The geological development of the area has led to the formation of significant raw material deposits. The historical extraction of the raw material deposits, encompassing both surface and underground mining techniques, has progressively impacted the groundwater regime, resulting in the formation of a newly established condition influenced by anthropogenic activities. This newly established conditions differ from the original natural conditions in terms of water balance and the groundwater composition. The extraction of raw material deposits was subsequently linked to the development of industry. The historical development of this raw materials-rich region, followed by industrial development and increasing population density, poses significant risks to the quantity and quality of groundwater. In the region at the boundary between the Bohemian Massif and the Western Carpathians, there are a number of examples of the negative impact of anthropogenic activity on groundwater, which are being addressed in all economically advanced countries around the world. The habilitation thesis focuses on three topics related to anthropogenic impact on groundwater. The first topic deals with the impact of raw material extraction on groundwater bodies. The impact on shallow aquifers is often endangered by the location of mining areas in the vicinity of important groundwater sources. Geological processes form significant accumulations of coarse-grained clastic sediments, which become important sources of the construction materials. Accumulations of coarse-grained clastic sediments also form key aquifers, whose hydraulic connection to surface streams and rivers is ideal for the establishment of groundwater extraction areas capable of supplying large cities. Anthropogenic risks arise from the hydraulic connection of gravel pits with adjacent aquifers and from the increase in evapotranspiration values in open water areas formed by mining, which can affect the overall water balance of groundwater bodies and the available natural groundwater resources for groundwater supply (P 1, P 2). Deep mining of raw materials primarily affects deep aquifers. Its impact on the groundwater is usually larger in spatial extent. When

mining works are hydraulically connected to overlying aquifers, it can also significantly affect the water balance of shallow aquifers and surface streams, leading to the desiccation of surface streams (P 3). The hydraulic connection of deep mining works with shallow aquifers is caused not only by mining-induced fractures. The groundwater flow in the hydrogeological massif environment, in which deep mining works are often located, is directly controlled by the non-homogeneities of the rock environment. These include not only the boundaries between different lithological rock types, but also tectonic features (P 4). When assessing the impact of flooded mines on surrounding aquifers and surface streams, numerical 3-D modelling of groundwater flow is a suitable tool which, if calibrated successfully, can precisely quantify the water balance and understand the processes that form mine water (P 5).

The second topic of anthropogenic impact is direct contamination of groundwater as a result of handling hazardous pollutants that leak into the aquifer. Groundwater is the main transport medium through which contamination spreads in the geological environment, and massive contamination can lead to long-term degradation of groundwater in terms of its potential use by humans. The transport processes that significantly influence the spread of contaminants are highly variable and directly related to the geological environment at contaminated sites. Natural attenuation processes, which reduce the intensity and spatial extent of contamination in groundwater, can occur with varying intensity (P 6). This is true even in the case of high concentrations of contaminants of exclusively anthropogenic origin, such as chlorinated aliphatic hydrocarbons.

The third topic deals with the possible anthropogenic impact on groundwater in deep sedimentary structures. Deep aquifers in buried sedimentary structures are very promising from many points of view. They may contain thermal waters with specific hydrochemical properties and have historically been used primarily for balneological purposes. Anthropogenic risks are mainly associated with their possible overexploitation. A current topic is the use of these structures as sources of geothermal energy, which, however, requires comprehensive knowledge of the formation and circulation of groundwater in these structures. Otherwise, there is a risk of permanent impact on the quality and quantity of groundwater. An example of such a promising structure with Mesozoic platform sediments, which also include their carbonate development, can be found in the border area between the Czech Republic and Austria on the south-eastern edge of the Bohemian Massif, where an aquifer containing thermal waters is buried under the sedimentary fill of the Carpathian foredeep. In the area of thermal water exploitation for balneological purposes in the spas of Laa an der Thaya (Austria) and Pasohlávky (Czech Republic), pilot stuy have been published defining the formation and circulation of thermal waters in this structure (P 7).

2 Impact of mining

The United Nations World Water Report from 2015 summarises that more than 2,5 bilion people worldwide depend solely on groundwater resources (Wada et al. 2014, Connor 2015). The groundwater resources are endangered not only by the climate change, but the direct human impacts, including aquifers overexploitation due to their inefficient use and/or rapid population growth; groundwater contamination is another specific problem (Aeschbach-Hertig and Gleeson 2012, Vörösmarty et al. 2000, Schwartz and Ibaraki 2011, Scanlon et al. 2007, Konikow and Kendy 2005, Wada et al. 2014). Despite the use of modern green technologies and efforts to achieve sustainable development of human society, the human population remains dependent on the extraction of mineral raw materials for the obtaining of primary resources. Mining in general can have a significant impact on the natural water systems. While underground mining tends to have less serious impacts on surface water features than an open pit surface mine has, all types of mining have the potential to directly disrupt groundwater flow (e.g. Booth 2002). Open pit mining is common mining strategy for the cases of shallow deposition of desired raw material and its economic feasibility.

2.1 Open pit mining

Gravel and sand are considered the second most extracted raw materials globally after water (Bendixen et al. 2021). Sand and gravel are among the most abundant materials on Earth, with a primary application in the construction industry as a fundamental ingredient. A substantial body of research has been conducted to quantify the reserves and extraction volumes of sand and gravel. These studies have consistently demonstrated that extraction far exceeds the capacity of geological processes to replenish these resources (Bendixen et al. 2019). The analysis of past and future global supply of sand and gravel (Sverdrup et al. 2017) predicts a global increase in the extraction of gravel and sand until 2200. Despite the growing importance of recycling, it is estimated that mining will still account for 20-30% of demand. The geological predisposition of sand and gravel accumulations in floodplains, terraces, and glacial sediment accumulations frequently spatially coincides with heavily urbanized areas characterised by high population density and development, as well as intensive agricultural activity. Peckenham et al. (2009) present an example from alluvial sediments in which open pits cover 26% of the total aquifer extent, posing significant impact to groundwater in adjacent aquifer. The impact of available groundwater resources on sustainable water supply in relation to the risks caused by the development of gravel pits is the subject of an assessment by Vanicek et al. (**P 1**). The following figure illustrates the historical, current and future projected extent of gravel pits, which has been predicted on the basis of the development of gravel mining extraction over time and areas with allocated gravel and sand deposits.

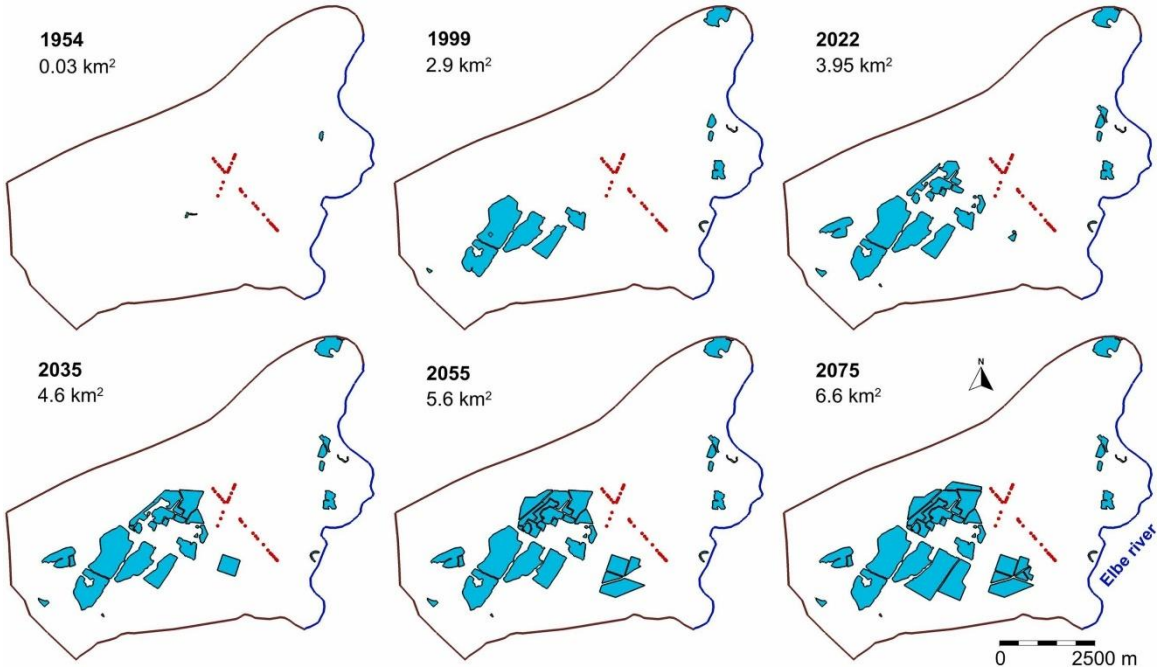


Figure 1: Observed (1954–2022) and estimated (2022–2075) expansion of pit lakes in the model area, red points show water supply wells of the Čeperka groundwater resource (P 1).

Sand and gravel resources are derived from various geomorphological settings such as beach deposits, streambeds, river floodplains and terraces, alluvial fans, and glacial deposits. Extraction of material from terraces is generally less impact than removing sand and gravel from active floodplains and stream channels (Kondolf 1997). A flat body of open groundwater in an excavation with maximum porosity, which communicates with groundwater in the surrounding aquifer, disrupts the original groundwater flow directions and hydraulic gradients (see Fig. 2).

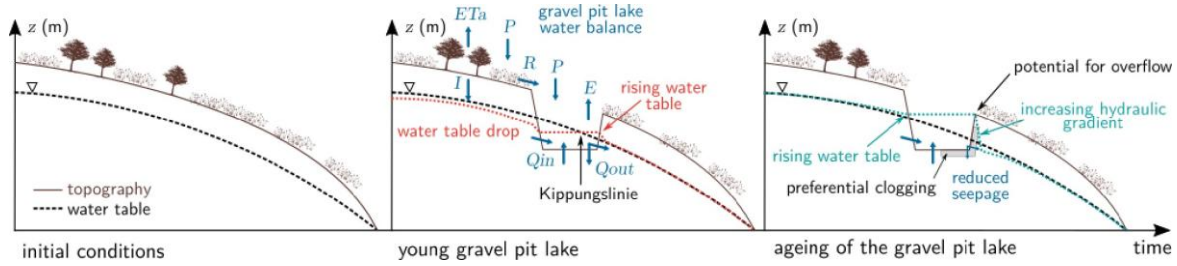


Figure 2: Gravel open pit lake–aquifer interactions over time (Jost et al. 2023) with the water balance members (precipitation P, actual evapotranspiration ETa , free water table evaporation E, diffuse runoff R, infiltration I , groundwater inflow Qin, groundwater outflow Qout.

The open gravel pits, which are filled by groundwater, may act as a sink for water from adjacent aquifers due to the direct evaporation from open water surfaces. This phenomenon is more prevalent in temperate and Mediterranean climates (Mollema and Antonellini 2016) and in dry years (Schanen et al. 1998). The main risk for aquifers is in possible water balance changes and changes in groundwater flow directions and levels, where the mining of sand and gravel is already in competing use with drinking water supply (Jost et al. 2023). Potential risks arise from a decrease in groundwater levels on the inflow side,

an increase on the outflow side, and evaporation from open areas, which causes a balance decrease in the volume of groundwater in the aquifer (Apaydin 2012, **P 1** , **P 2**). According to the Marsland and Hall (1989), the concentrated existence of a large number of gravel pits in a single aquifer can lead to a demonstrably measurable decrease in the groundwater table level.

The impact of mining pits on the groundwater regime has been demonstrated by pilot hydrogeological studies based on field measurements (Wrobel 1980, Morgan-Jones et al. 1984, Gravost 1988, and others), expecting the regional impact to aquifers. These studies have shown that the formation of inflow and outflow sides in mining pits depends on their orientation relative to the direction of groundwater flow. Example of groundwater flow disruption in surrounding shallow quaternary aquifer on the example of the Mohelnice – Moravičany site (**P 2**) proved rather local than regional impact. However, the impact was limited due to the close aquifer boundary condition (Morava River); the obviously smaller extent of outflow side compared to inflow side extent was driven by the open pit drainage vie weir overflow. The extent of the inflow and outflow sides are shown in Fig. 3.

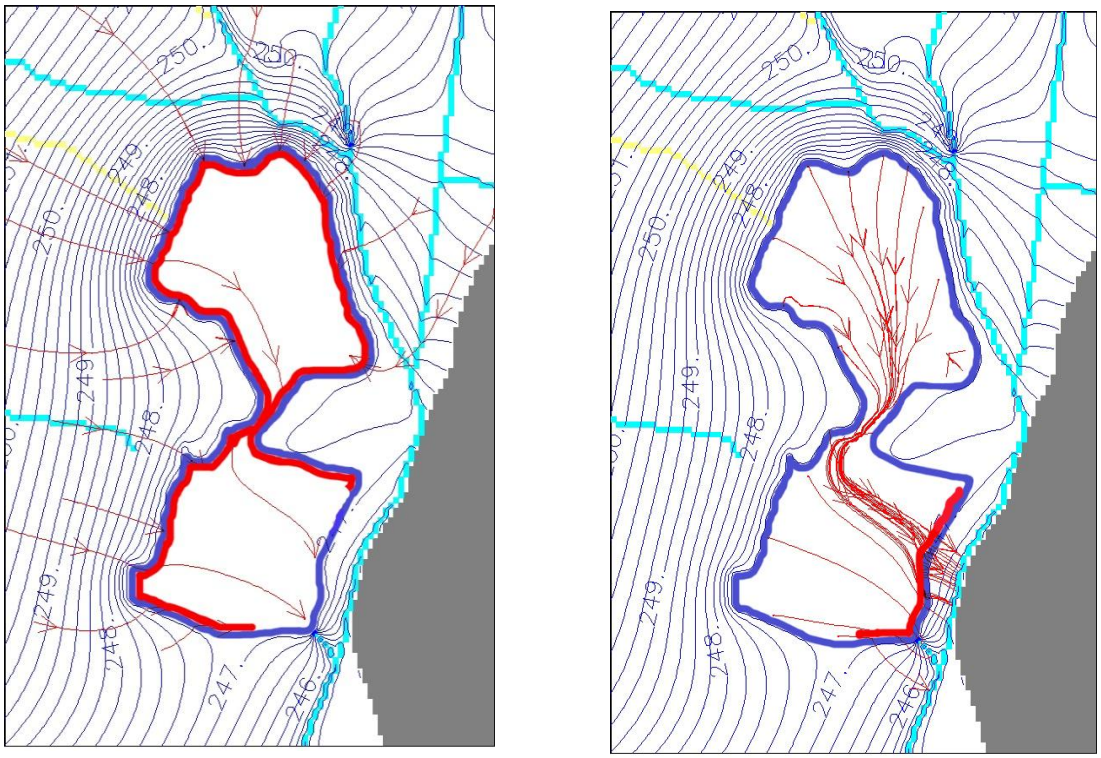


Figure 3: Location of inflow (left) and outflow (right) sides of the gravel open pit Mohelnice - Moravičany with equipotential lines (blue thin lines) and flow directions (brown arrows).t hick red lines show the inflow and outflow sides, thick blue lines show the open gravel pit boundary (modified after Červenková 2005 and Potočárová 2007).

When assessing the anthropogenic impact of gravel pits on groundwater, the absence of data prior to extraction is often problematic. Similarly, data on the impact after the opening of a new excavation or the expansion of an existing one are not available either. Empirical formulas have been derived in order to quantify the impact of gravel pits on groundwater levels (e.g., Wrobel 1980, Marinelli and Nicolli 2000, Yihdego 2017). However, a comparative analysis with numerical models has exposed the limitations and

inaccuracies of analytical approaches (Vrzel et al., 2023). Conversely, numerical models have been shown to be capable of achieving accurate results and can be used in variable geological environments involving not only the extraction of gravel and sand but also other raw materials (e.g., Rapantova et al. 2007, ERMITE-Consortium 2004, Maliva et al. 2010, Brown and Trott 2014, Krčmář and Sracek 2014, Fernández-Álvarez et al. 2016). The authors consistently highlight the necessity to calibrate models with real measured data, incorporating, in addition to the conventional approach utilising groundwater levels as monitoring parameters, inflows into mine workings. The accuracy of commonly used ModFlow-based models was tested by Lu et al. (2021), revealing potential inaccuracies in the numerical solution at the interface between an open space filled with groundwater and the porous environment of the aquifer, even when using the LAK3 module (Merritt and Konikow 2000). This manifests as inaccurately simulated levels in close proximity to the interface. However, higher accuracy can be achieved by modifying the basic model grid. A frequently employed methodology is to simulate the free space filled with groundwater as a zone with extremely high values of horizontal and vertical hydraulic conductivity (Anderson et al. 2002, Chui and Freyberg 2008, Yihdego and Becht, 2013). This provides results that are fully comparable to those obtained using LAK modules (Hunt et al. 2003) and other modules developed for simulating open water areas (Cheng and Anderson 1993). The free space simulation by the high hydraulic conductivities values in cells corresponding to the open pit was used in the 3-D numerical groundwater flow model of the gravel pits at the Mohelnice – Moravičany site (**P 2**). The maximum groundwater table decline in cross-section is -1,7 m; the maximum ground water table rise is +1,0 m (see Fig. 4). A significant factor influencing groundwater communication in the interior of gravel pits with adjacent aquifers is the possible existence of a clogged layer on the banks and bottoms of gravel pits. Fine-grained material may originate from the washing out of fine-grained fractions directly during extraction, but it may also be of biogenic and chemogenic origin. The processes of clogging layer formation are most intense at the beginning of extraction and gradually become less intense, partly due to a decrease in groundwater inflow as a result of the clogging itself (Jost et al. 2023). The maximum thickness of clogged layers occurs closer to the drainage sides; according to Schanen et al. (1998), they reach a thickness of 0,5–1,5 m and a hydraulic conductivity decreasing to values in the order of 10^{-8} m/s. Numerical simulations of the effect of the clogged layer indicate that with increasing clogging (decreasing hydraulic conductivity of the clogged layer, or clogging coefficient), the area of the inflow side of the gravel pit increases and, at the same time, the underground inflow through this area decreases (Genereux and Bandopadhyay 2001).

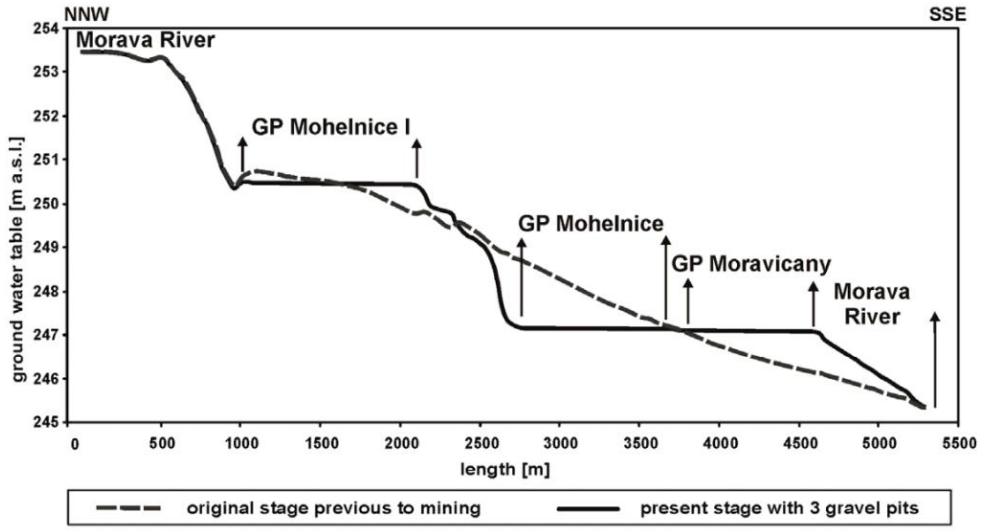


Figure 4: Changes in groundwater table resulting from gravel mining in cross-section parallel to principal groundwater flow directions (P 2).

The exposure of groundwater bodies to atmospheric conditions frequently results in a change in the oxidation-reduction conditions within the groundwater that percolates into gravel pits resulting in possible precipitation of mineral phases and their sedimentation within the gravel pit environment. This phenomenon is particularly evident in shallow aquifers characterised by elevated concentrations of dissolved Fe and Mn. At the Mohelnice – Moravičany site, the geochemical modelling indicated precipitation of a few minerals in open pits (**P 2**). Compared with the background groundwater chemistry, there is precipitation of 140 mg of calcite, 3 mg of amorphous Fe(OH)3, 0,2 mg of pyrolusite from 1 litre of water and increase of pH values from 7,1 to 8,2 in the open pit. Currently, Fe and Mn concentrations in ground water decrease from 1,5 to $2{,}5\times10^{-9}$ mg/L and from 0,15 to $4{,}3\times10^{-12}$ mg/L. Ground water chemistry in supply wells close to the outflow side of the gravel open pits confirms the results of this geochemical modelling. The interaction between groundwater and atmospheric conditions results in the precipitation of Fe and Mn oxyhydroxides, leading to a substantial decline in the total Fe and Mn content in groundwater discharging from the gravel pit. This development can prove advantageous for subsequent raw groundwater abstraction, as it facilitates economically feasible treatment processes. Conversely, an increased presence of biogenic sediment has been observed to result in elevated levels of certain detrimental indicators in groundwater on the outflow side (e.g., DOC, bacterial colonies) in comparison to the composition of groundwater at the inflow to the gravel pit. However, the number of microorganism colonies was found to be significantly lower in samples from the gravel pit itself, thereby demonstrating the filtration capabilities of the collector's permeable environment. Some authors also report higher water quality in terms of concentrations of components leading to eutrophication compared to groundwater in adjacent shallow aquifers. A notable observation was the decline in nitrate and phosphate concentrations (Muellegger et al. 2013, Bertleff et al. 2023). A positive impact on the ecosystem can be identified in the increasing biodiversity (Seelen et al. 2021).

Impact of evapotranspiration

Winter (1999) has highlighted the substantial impact of open water bodies connected to groundwater hydraulically, with effects that can be regional in scope and which can fundamentally modify the characteristics of groundwater flow. A global assessment of evapotranspiration (ET) changes based on remote sensing methods (e.g., Zhao et al. 2022, Cooley et al. 2021) has revealed a global increase in the volume of water in the hydrological cycle, released by evaporation from lakes (including artificial ones) and an overall increase in the area of artificial lakes. However, it should be noted that the applicability of these data to specific locations is limited. From a climate change perspective, ET is a critical parameter whose changes can have a significant negative impact on the water balance of lakes and, given their hydraulic connection to adjacent aquifers, also on natural groundwater resources. Local studies show that changes in ET are primarily influenced by local climatic conditions and that fluctuations in ET values are related to significant meteorological phenomena (Spence et al. 2013, Friedrich et al. 2018). It has been demonstrated that the water balance, and consequently the overall impact of gravel pits on groundwater, can be significantly influenced by ET. Comparison of the ET rates of lakes versus native vegetation is frequently complicated by the limited amount of data available, particularly for upland vegetation (Maliva and Hopfensperger 2007, Maliva et al. 2010). In addition to the dominant component corresponding to evaporation from the free water surface, transpiration of aquatic plants can also contribute to ET. The processes previously mentioned are influenced by a number of factors. Firstly, the meteorological characteristics of the site must be taken into consideration. Mollema and Antonellini (2016) predict a negative impact on the water balance of aquifers in all gravel pits in temperate and Mediterranean climate zones, as ET values from gravel pits exceed AET values for vegetation cover but are still lower than PET values. It is not possible to generalise estimates of water losses from gravel pits due to the local variability of parameters affecting the water balance. Furthermore, these estimates are influenced by current climatic conditions. As reported in Schanen et al. (1998), the daily water balance losses in gravel pits are estimated to range from 6-11 m3/ha. In contrast, at the Mohelnice – Moravičany site, the lower evaporation losses of 3,5 l/s were calculated during the 3-D numerical groundwater flow model calibration (**P 2**), which in given extent of the open pit, corresponds to a value of 4 m3/ha per a day, probably due to limited seepage via clogging layer. Reported average water loss of 6 L/s/km^2 at the Čeperka site (**P 1**) equals to daily loss of 5,2 m3/ha.

In arid and semi-arid regions, the ET rates frequently exceed the rates of precipitation, with evaporation losses from open surfaces ranging from 1,300 to 1,700 millimetres per year (Scanlon et al. 2006). This corresponds to losses of up to 47 m3/ha per a day. Furthermore, gravel pits become zones of groundwater drainage in such a cases. The consequences of this phenomenon has a negative impact not only to groundwater tables decline, but also to an increase in groundwater mineralisation. Marsland and Hall (1989) demonstrated the negative impact of gravel pits due to increased evaporation from open water areas, which, combined with the impact of water extraction, led to an increase in the salinity of the groundwater extracted in the water supply structure. Similar results proving the direct impact of evaporation from open water table to chloride concentration was found at the Čeperka site in particular isotopic study (Říčka et al. 2021). Evidence from stable isotope analysis of water samples indicates that chloride concentrations are increasing in response to the process of evaporation (Fig. 5).

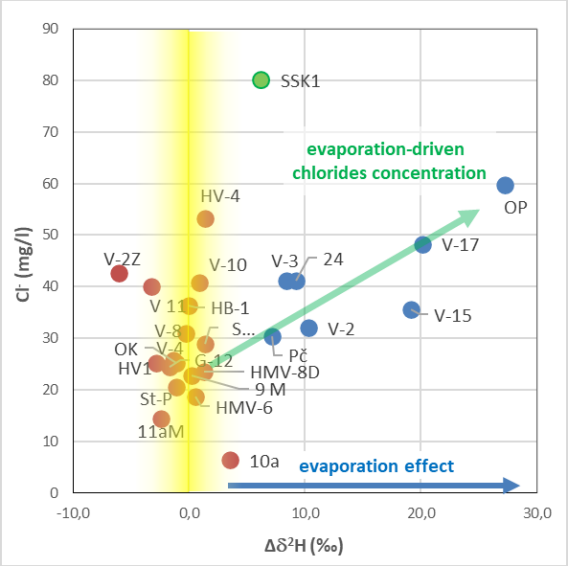


Figure 5: Chlorides concentration in evaporation-affected groundwater samples. Red points show samples with no impact of evaporation, blue points evaporation-affected samples. The Δd²H values are compared to background composition.

Healy and Cook (2002) provide a comprehensive overview of the methods employed for the determination of ET, with a particular focus on the analysis of groundwater level fluctuations. Comparison of the ET rates of lakes versus native vegetation is frequently complicated by the limited amount of data available, particularly for upland vegetation (Maliva and Hopfensperger 2007). The development of isotope hydrology has enabled the conduction of numerous studies that have demonstrated the enrichment of water in gravel pits with relatively heavier isotopes as a result of the evaporation of water molecules from the free water surface (Mazor 2003, Fette et al. 2005, Bertleff et al. 2003, Seebach et al. 2008, Sánchez-España et al. 2014, **P 1**). The method has also been proven to be conclusive in the case of brackish water bodies containing a mixture of shallow groundwater and water of marine origin (Mollema et al. 2015).

The impact of open gravel pit to an aquifer where the ongoing gravel mining is competing with water supply resource for 100.000 inhabitants have been studied at the Čeperka site (**P 1**). Sustainability of the water resources has been solved in the context of climatic change and progressive mining. The 3-D numerical groundwater flow modelling of quaternary aquifer have been used to determine the current stage, with the use of borehole groundwater levels and surface discharges during calibration process (see Fig. 6). The future model scenarios of (a) increasing extent of open pits and (b) changes in climatic characteristics were used to clearly conclude that future sustainable water resources at the site might drop. Within the reasonable range of climate scenarios, the specific water loss in the water table is predicted to increase from the current rate of 6 to 7,2 L/s/km2 by 2075 due to increasing ET rates, assuming a medium climate scenario. The concurrent expansion of open-pit mining is predicted to result in a 6% decline in sustainable groundwater resources by the year 2075 (see Fig. 7). In consideration of the alterations in aquifer boundary conditions occasioned by climatic variations (water levels in the aquifer and the Elbe River), a 18% decline in sustainable water resources is predicted, from the present 150 to 124 L/s. This finding has fundamental implications for the sustainable

management of the groundwater resource, where the current long-term average water abstraction of 132 L/s could be endangered in the near future.

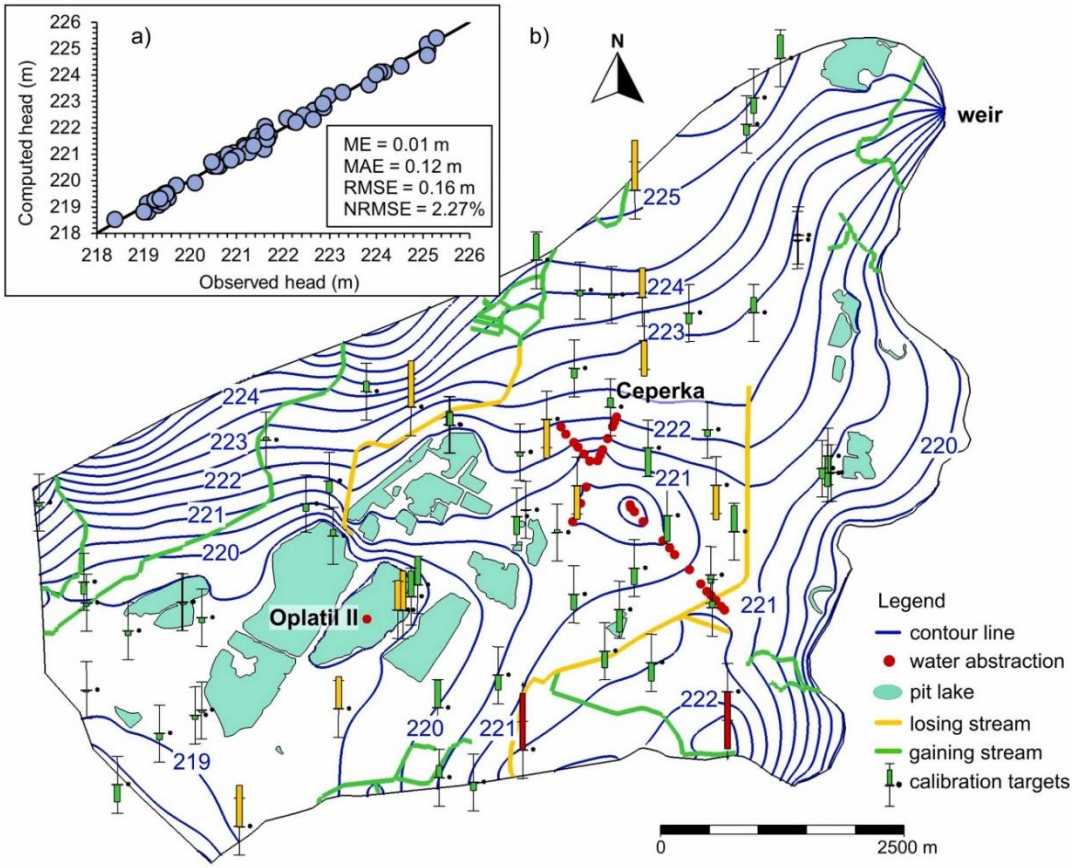


Figure 6: 3-D model result for current stage scenario of the Čeperka site. Comparison of computed and observed hydraulic heads (a) and spatial distribution of the simulated hydraulic heads in a 0.5 m interval (b). The range of residual error is green < 0.2 m, yellow < 0.4 m, and red > 0.4 m (P 1).

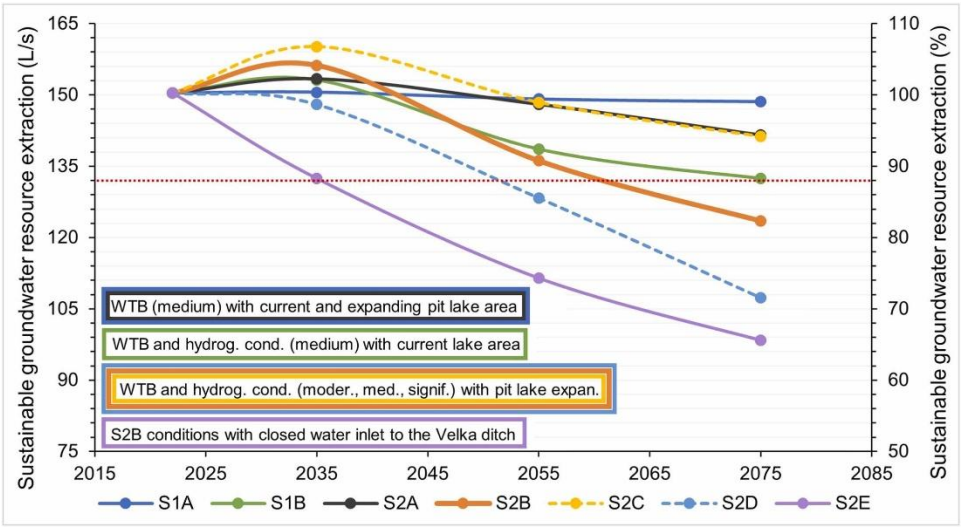


Figure 7: Evolution of sustainable groundwater resource in simulated scenarios, highlighted curve represents the most realistic scenario, the red dotted line represents current long-term water demand (P 1).

Expected regional impact of gravel open pits to aquifers has not been confirmed. In the context of the observed impact on water levels, the influence of gravel pits cannot be characterised as having a regional effect but rather must be considered local. Evidence from field observations indicates that the impact on water levels exhibits a range of hundreds of metres to several kilometres.

2.2 Deep mining

The extraction of mineral resources by means of mining has a significant impact on both groundwater and surface water. Evidence of this phenomenon is not only apparent during the active mining process, but also in the long-term periods that extend decades after mining has ceased (see Younger et al. 2002, ERMITE-Consortium 2004). The impacts of mining are often perceived negatively, both in terms of contamination of groundwater and surface water and in terms of influencing the original regime of water elements in the landscape.

A number of studies evaluating the hydraulic connection between mine workings and surrounding aquifers have been conducted with the objective of preventing fatal mining disasters caused by groundwater inrush into mine workings. The importance of numerical models in evaluating hydrodynamic conditions in mining areas is well-documented, with the capacity to characterise the connection between overlying aquifers and mine workings, and the prediction of water inrushes being a key benefit (Li and Zhou 2006, Wu and Zhou 2008, Mu et al. 2020). The heightened risks are associated with excavation-induced water inrush (Hudson and Harrison 2000), which is predominantly linked to excavation-induced alterations in stress and deformation of the rock environment, consequently resulting in an increase in the permeability of the rock body (Huang et al. 2019).

In recent decades, significant attention has been devoted to the study of this particular issue of hydromechanical coupling processes at the interface between geotechnics and hydrogeology. This research has been conducted not only in relation to mining, but primarily in the context of evaluating the safety of deep radioactive waste repositories. The extent of excavation disturbed zones (EDZ) is typically limited to a few metres in crystalline rocks, metamorphic and diagenetically consolidated clayey sediments (Hudson et al. 2009, Tsang et al. 2005, Olsson et al. 2009, Autio et al. 2011). Documented increases in hydraulic conductivity values are up to six orders of magnitude higher than in the surrounding undisturbed rock mass (Bernier et al 2007, Bossart et al. 2002, Hata et al. 2024). Given their spatial extent, natural geological structures in the rock mass can influence groundwater flow over incomparably greater distances. Their mutual connectivity and reach, typically in the hundreds of metres to units of kilometres, also pose an additional risk from a regional perspective in terms of hydraulic connection with highly water-bearing structures or surface streams. The communication of mining operations with tectonic faults is invariably associated with the permeability and water saturation of these structures (e.g., Bense and Van Balen 2004, Bense and Person 2006). The hydraulic properties and lithology of these faults differ considerably from those that are typical of the EDZ (Caine et al. 1996). The presence of clay minerals in tectonic faults is often indicative of long-term groundwater flow. The presence and behaviour of these elements under

various pressure and saturation conditions have been shown to have a significant effect on the overall permeability of a tectonic fault (Bense and Van Balen 2004, Yu et al. 2021). The geomechanical–hydraulic coupled processes in mining induced faults may provide streambed cracking and vertical leakage where stream or river channels cross the tension zones. The faults reactivation both by mining and dewatering activities in Great Britain summarizes Donnelly (2009); on examples of tenths worldwide coal mining sites in review from 2009 (Donelly et al. 2008). Younger and colleagues provide the broader hydrogeologic framework: "caving" methods such as longwall increase vertical connectivity and can hydraulically link shallow aquifers and streams to mine-affected fracture networks, enabling capture of surface water in dry states and localized exfiltration when gradients or heads rise (including during mine-water rebound). They also codify the integrated monitoring and tracer approaches now standard in both research and regulatory practice (Younger et al. 2002, ERMITE-Consortium 2004). The field programs conducted during reach-scale profiling in Ohio–Pennsylvania–West Virginia on undermined Appalachian streams have demonstrated discharge deficits in surface streams and, in dry conditions, even temporary disappearance of surface flow (Wade 2005, OSMRE 2005). Independent evidence from the Southern Coalfield (NSW, Australia) documents the same mechanism in a contrasting geologic setting, where fractured sandstone and streambed cracks divert surface water to shallow fracture systems under low flows (Jankowski 2008). Regulatory syntheses in Pennsylvania corroborate the prevalence of these impacts across undermined stream networks. The Act 54 assessments catalogue stream segments affected by flow loss, pooling, and fracture-related hydraulic disconnection in longwall areas and use these categories operationally in permitting and compliance (PA DEP 2019, PA DEP 2024). While definitions and metrics have evolved between reports, the typology and case inventories are consistent with the low-flow losing/high-flow gaining dynamics inferred from process studies (Wade 2005, Jankowski 2008). Detailed analyses show that fracture opening and bedding separation increase effective fracture porosity and create new void space capable of capturing baseflow and depressing shallow heads; partial recovery depends on time-varying fracture closure and recharge typical for impact of longwall mining (Booth 1999, Booth 2007). A recent review constrains expected fracture heights and connectivity envelopes above panels, clarifying where streambed cracking and vertical leakage are most probable (Hebblewhite 2020).

In a detailed study focused on determining the causes of abnormally high outflows from flooded mining works in the Rosice-Oslavany black coal mining district, Kuchovsky et al. (**P 3**) demonstrated the effluent characteristics of all surface streams in the overburden of the mining area. The location of loosing sections is obvious from Figure 8.

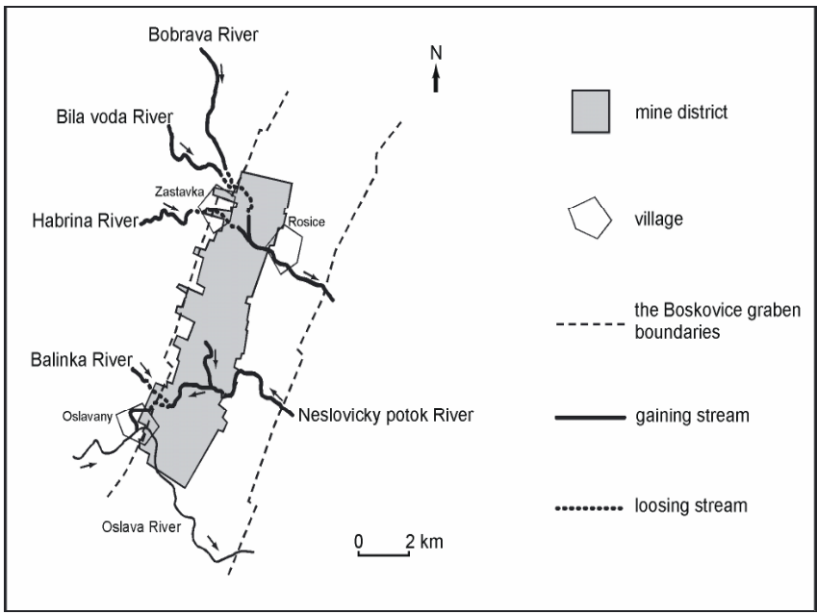


Figure 8: Location of loosing and gaining stream section in the Rosice-Oslavany black coal mining district (P 3).

It was observed that losses occurred in all water stages, with riverbeds undergoing desiccation during periods of low water levels. The losses amounted to 15-40 L/s, constituting a substantial proportion of the total discharge from the mine, which ranges from 35-80 L/s following the mine complete flooding. The measured discharges along the stream channels are illustrated in Figure 9.

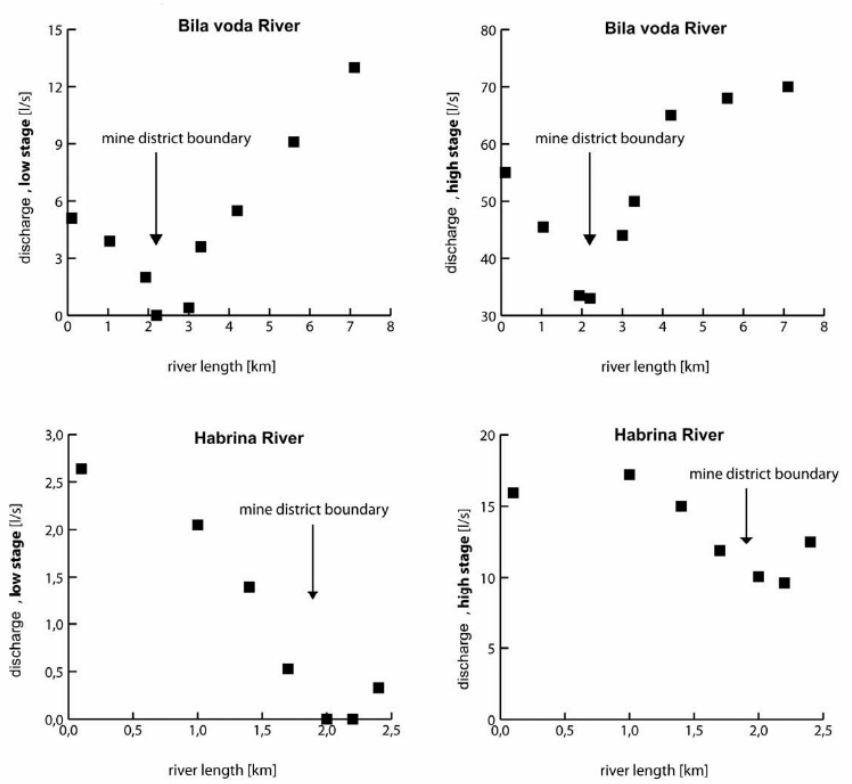


Figure 9: Stream discharge changes along channels in the Bílá Voda and Habřina Rivers (P 3).

Many deep mines are located in crystalline rocks or sedimentary complexes, which, due to their age and metamorphic processes during geological development, exhibit the characteristics of a hydrogeological massif, containing various sets of tectonic structures. Tectonic structures are known to cause heterogeneity and anisotropy in the hydraulic conductivity of aquifers. This results in a number of geological processes, including groundwater flow through rock massifs. This process has been described in a number of studies, including those by Levens et al. (1994) on the seepage and discharges into a mine in metamorphic rocks (quartzite and argillite), Douglas et al. (2000) on crystalline rocks as a natural analogue of a deep repository for high-level radioactive waste, Evans et al. (1997) on samples of drill cores from granitic rocks, Caine et al. (1996) on brittle faults with a cataclasite-rich fault core, and Rawling et al. (2001) on the typically barrier characteristics attributed to permeability reduction as a result of the ductile folding of clay along the fault plane and cataclastic deformation, which reduces permeability in the damage zone around the fault core. In their 2022 study, Olaka et al. provide compelling evidence, substantiated by a comprehensive array of hydrochemical indicators and isotope studies, that less permeable tectonic structures oriented perpendicularly to groundwater flow directions exert a substantial influence on the flow and seepage velocities of groundwater in disparate regions of the aquifer. Bense et al. (2013) provide a comprehensive overview of the issues associated with fault zone hydrogeology, drawing upon a series of case studies for illustrative purposes.

Methodological approach to investigate the impact of tectonic and structural features on groundwater flow is to track temperature variations resulting from changes in rock permeability (Anderson and Fairley 2008, Bense et al. 2008, Read et al. 2013). Observations based on tracking the thermal anomalies in aquifers are conventionally employed in geological structures exhibiting elevated heat flow. As demonstrated by Ricka et al. (**P 4**), the method was found to be effective in delineating groundwater recharge zones within crystalline rock aquifers in the Uranium mining district of Rožná, Czech Republic. In this particular study, the temperature contrast between groundwater and the cooled earth's surface was utilised. The impact of surface morphology, rock types and tectonic structures on groundwater flow was observed. It is expected that the morphology effect will cause the main principal flow directions (see Fig. 10). However, the frequent presence of four main fault systems (see Fig. 10) was expected to have a significant impact on groundwater flow.

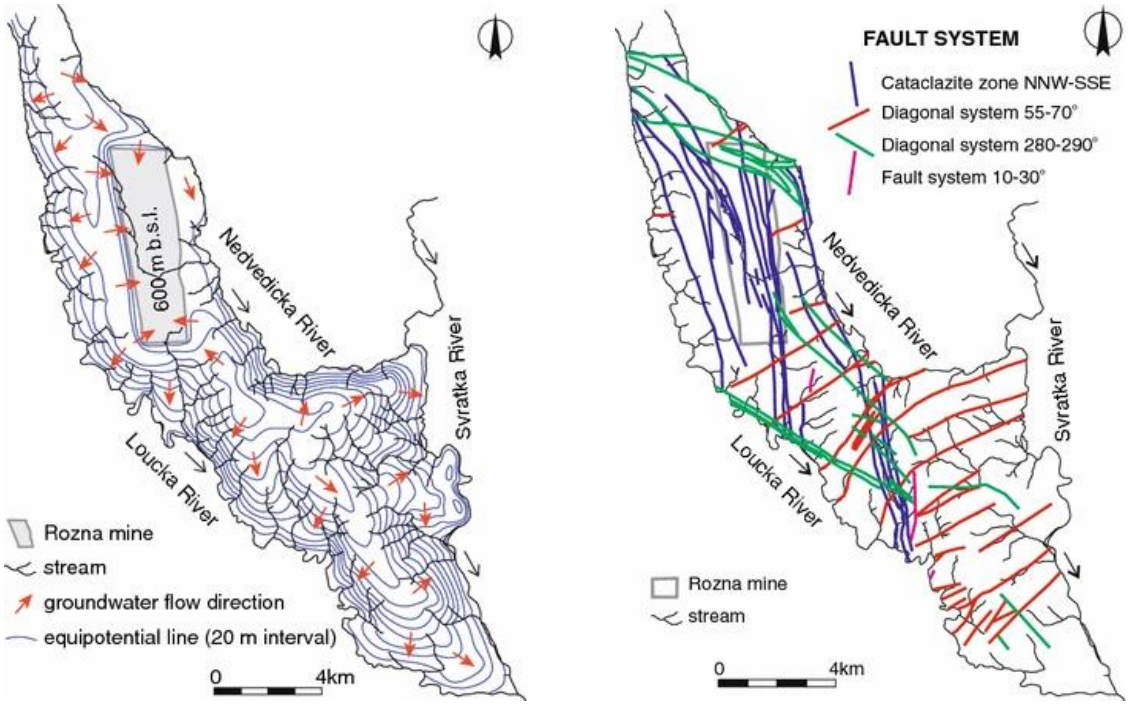


Figure 10: Conceptual morphology-driven groundwater pattern (left) and fault system map (right) in the Uranium Rožná mining district (P 4).

The morphological setting, predetermined by the syncline-anticline geological setting, is illustrated in Figure 11. A comparison of temperature and electrical conductivity (EC) values in the northern and middle parts of the area was made, which confirmed the importance of deeper regional groundwater flow and the minor importance of local groundwater flow in the northern part of the area studied. The highest frequency of drainage positions was identified in the southern part of the area.

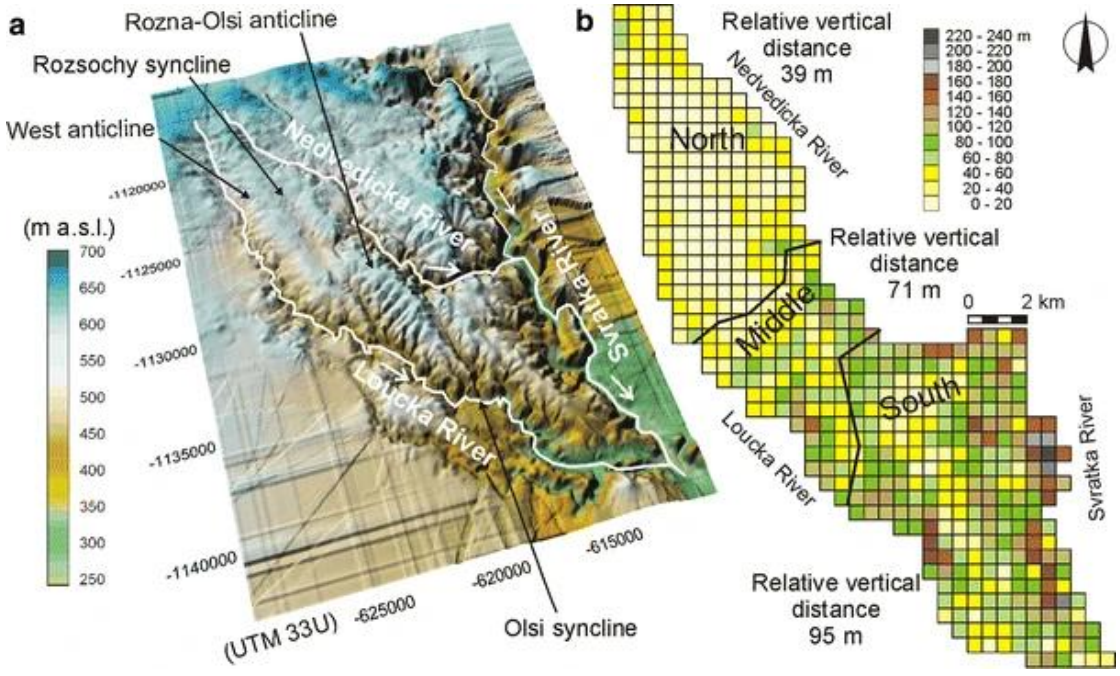


Figure 11: Surface morphology (a) and model of relative vertical distance (b) (P 4).

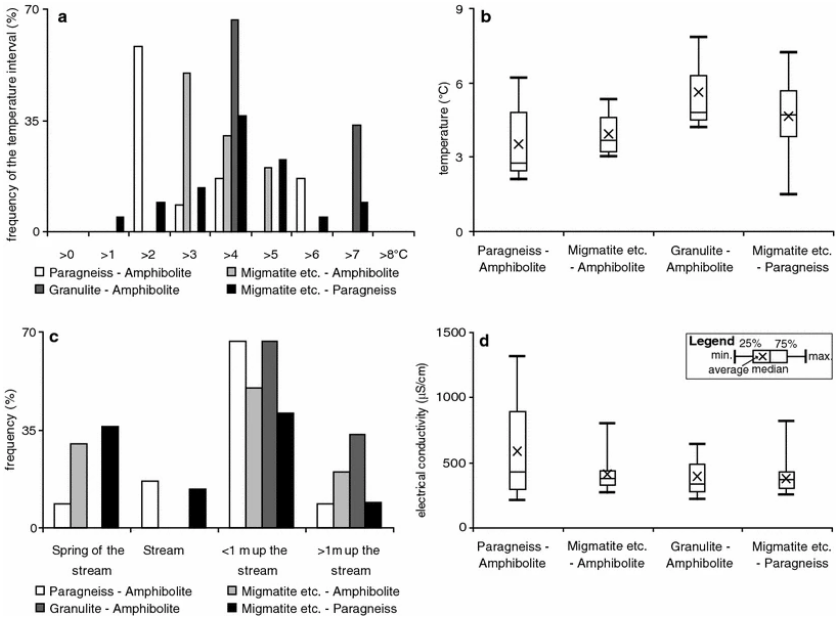


Figure 12: Discharge points within the Rock type contact factor: (a) frequency distribution, (b) statistical parameters of temperature, (c) frequency distribution of discharge types and (d) statistical parameters of electrical conductivity (P 4).

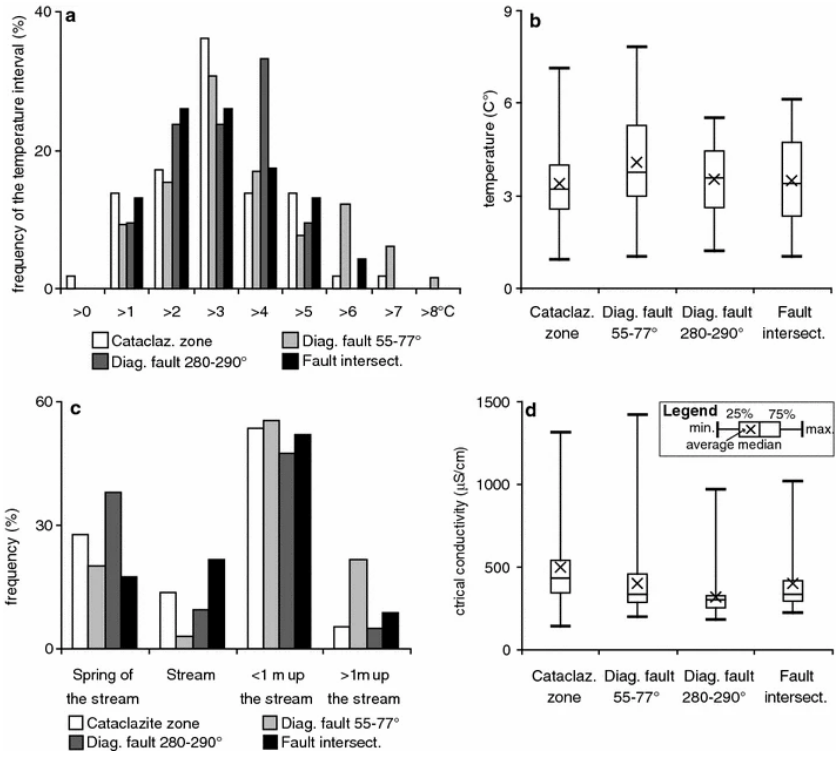


Figure 13: Discharge points within Fault system factor: (a) frequency distribution, (b) statistical parameters of temperature, (c) frequency distribution of discharge types and (d) statistical parameters of electrical conductivity (P 4).

Non-homogeneities formed by geological settings have been demonstrated to have a significant impact on groundwater flow characteristics. Surprisingly, the impact of the geological setting (comprising different rock types) was found to be comparable to the impact of tectonic structures. The relatively deeper and faster groundwater flow is typical of zones where granulites, migmatites, orthogneisses, and granites form the aquifer. It has been determined that the most significant geological feature in terms of groundwater drainage is the occurrence of amphibolites in contact with other rock formations, meaning the amphibolites are the less permeable rock type. In the context of the observed fault systems, the impact of the diagonal fault structure (55°–70°) on groundwater flow was identified as the most significant. This phenomenon can be attributed to the higher permeability of this particular structure in comparison with the other tectonic structures in the area under study. Evidence suggests that, in accordance with the lower EC values and higher temperatures observed, groundwater is being drained from the morphologically higher parts of the catchment. The potential of the diagonal fault structure, with a range of 55°–70°, as a drainage system is obvious. It is proposed that the observed results might be utilised to refine the 3-D numerical model for mine flooding in future studies.

Heterogeneity is typical feature in coal basins: layered sedimentary units and coal seams produce multi-aquifer systems with strong vertical contrasts in hydraulic properties and anisotropy, further complicated by faults and mining-induced fracturing and underground excavation of mine works. Foundational syntheses emphasize that such media rarely behave as uniform porous bodies; instead, permeability is stratabound and compartmentalized, and mining alters hydraulic connectivity and heads both locally and regionally. These features govern capture zones of dewatering and the partitioning of recharge among shallow versus deeper flow systems (Younger et al. 2002, Booth 2002). Mining superimposes new heterogeneity by opening fracture networks and bedding separations. Over and around longwall panels, vertical permeability and effective fracture porosity increase, re-routing flow through preferential pathways and changing aquifer conditions; beyond the mined panel, secondary drawdown propagates laterally within more transmissive layers, redistributing gradients and capture (Booth 2002). As Rapantová et al. (2007) and ERMITE-Consortium (2004) have demonstrated, the utilisation of groundwater flow modelling tools is a pivotal component in the forecasting of future mining and post-mining activities. Adams and Younger (2001) provide examples of the use of different approaches in modelling mine flooding. Depending on the extent of the mine workings, they summarize the possibilities of using physical models in small-scale mines up to large areas, with models combining 3-D pipe networks for the principal main mine works and 3-D porous media representing the host rock. Bozan et al. (2022) present a conceptual comparison of the effects of rock material characteristics and climatic conditions on the development of the water level in a mine during its drainage and subsequent flooding, using numerical modelling. However, these authors also highlight the necessity of considering the specifics of individual locations when evaluating the impact of mining on hydrodynamic conditions. In classic Central European coalfields, heterogeneity is layered at formation scale. The Upper Silesian Coal Basin, for instance, comprises several hydraulically distinct complexes; high-permeability sandstones are separated by low-K units, while fault zones locally modify flow paths and boundaries. As a results, this setting delineates the geometry of dewatering cones and the pathways for solute migration and saline water movement during mine operation and after mine closure (Rogoż 1987, Cmiel

et al. 2012).Where regional low-permeability formations are present, they can act as hydraulic barriers that compartmentalize mine-affected flow, which has been shown in the Ruhr District in Germany on the example of the Emscher marls Formation (Genth et al. 2024, Coldewey et al. 2014) integrated into 3-D models to quantify porosity/permeability profiles and evaluate barrier performance during mine-water rebound. This is in coincidence with older studies reporting very low fault-zone permeabilities within these marls. The interconnection of mine works has been shown to have a fundamental impact on the hydrogeological conditions of the surrounding area (Gonzales-Quiros et al. 2024). However, following the flooding of mine works, a stable groundwater flow regime is established, characterised by intense flow through the flooded mining operations. The overall impact on surface water differs significantly from that during active mining. No observable hydraulic connection between the surface stream and the mine has been identified (Gonzales-Quiros et al. 2024). In contrast, during the process of mining, a substantial local hydraulic connection with the surface stream was observed during the implementation of mine drainage.

Kuchovsky et al. (**P 5**) present a study of the regional impact of a flooded mine on adjacent aquifers using a 3-D numerical model of the Rosice-Oslavany black coal mining district in the Permo-Carboniferous sediments of the Boskovice Graben unit. Simplified geological setting is shown in Fig. 14. For the numerical groundwater flow modelling, the conceptualisation of geological setting is always necessary (Fig. 15).

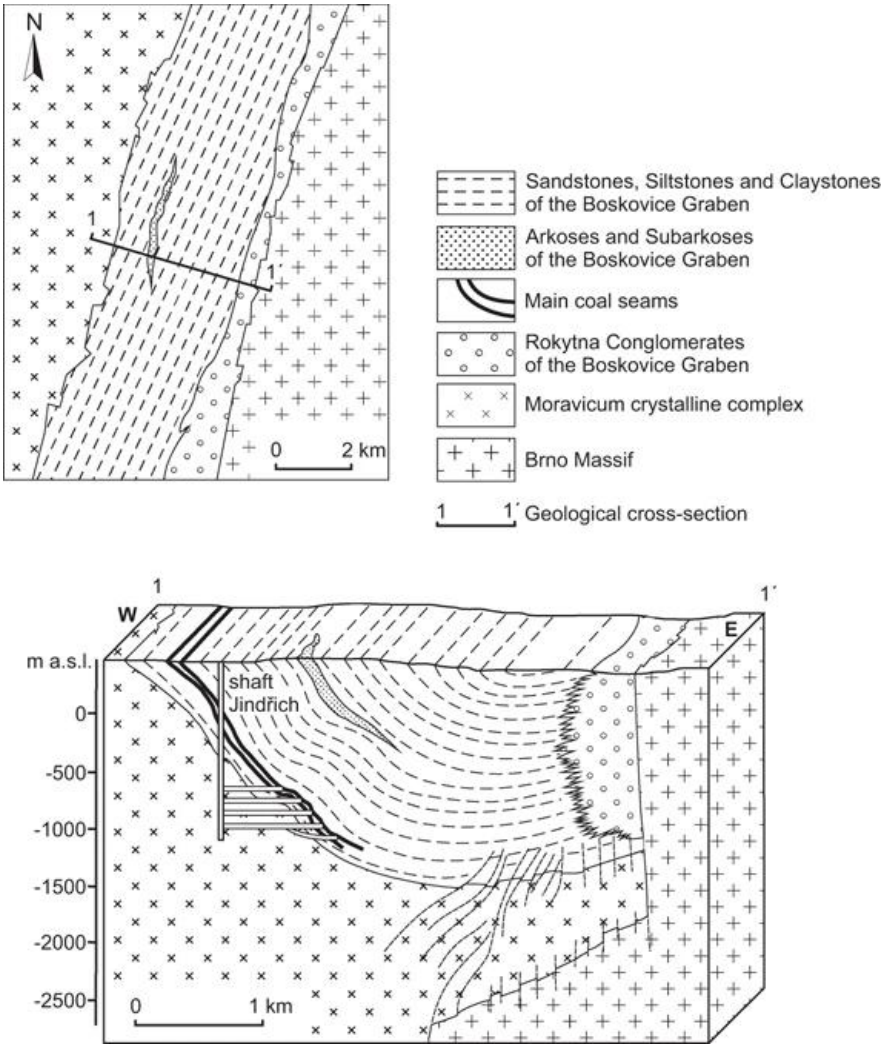


Figure 14: Geological setting of the Rosice-Oslavany black coal mining district (P 5).

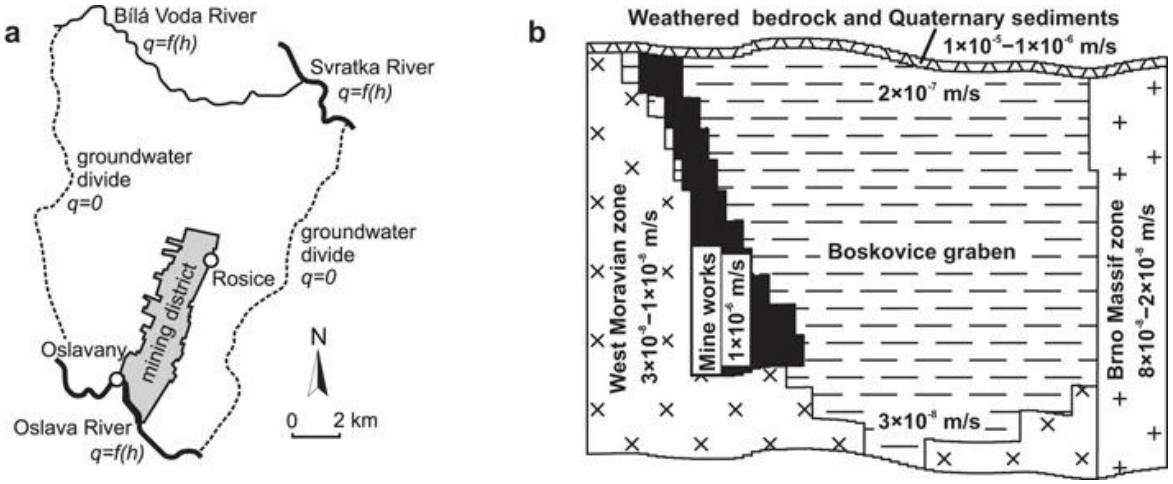


Figure 15: 3-D model boundary conditions (a) and conceptualization of geological setting for 3-D model (b) of the Rosice-Oslavany black coal mining district (P 5).

The calibrated hydraulic model demonstrated that the source of the elevated inflow into the flooded mine is the hydraulic connectivity of the mine works with all five surface streams located above areas of coal seam outcrops, mining induced fracture, and regionally significant tectonic lines. The study demonstrated the ability to use an equivalent-porous-medium model at a regional scale even in the case of aquifer heterogeneity, provided that an extensive dataset from field measurements is available (Fig. 16).

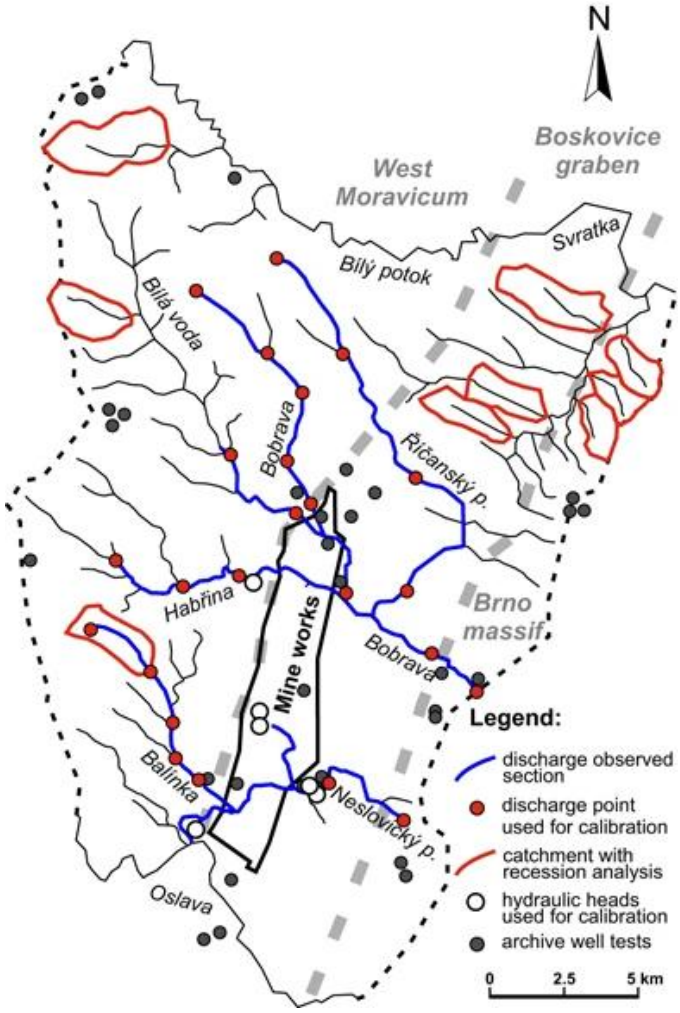


Figure 16: Observation points for regional 3-D groundwater flow model of the Rosice-Oslavany black coal mining district (P 5).

Model was also used to reconstruct the hydrogeological setting of the pre-mining stage, proving that the mining activities themselves are responsible for loosing streams formation. The measured drops in stream discharges were used to calibrate the hydraulic parameters of the fault zones. The vertical hydraulic conductivity values increase by over two to three orders of magnitude in comparison to mining non-affected parts of the aquifer. In general, the water balance demonstrates that, in steady-state conditions, 46% of the total mine water discharge of 59 l/s originates from the surface streams. The groundwater flow model confirmed that mining has significantly influenced the local groundwater system, but that it has had a relatively small effect on the hydrology of the deep

groundwater flow system, based on the negligible changes observed in the regionally important river watersheds (see comparison of equipotential lines in Figure 17).

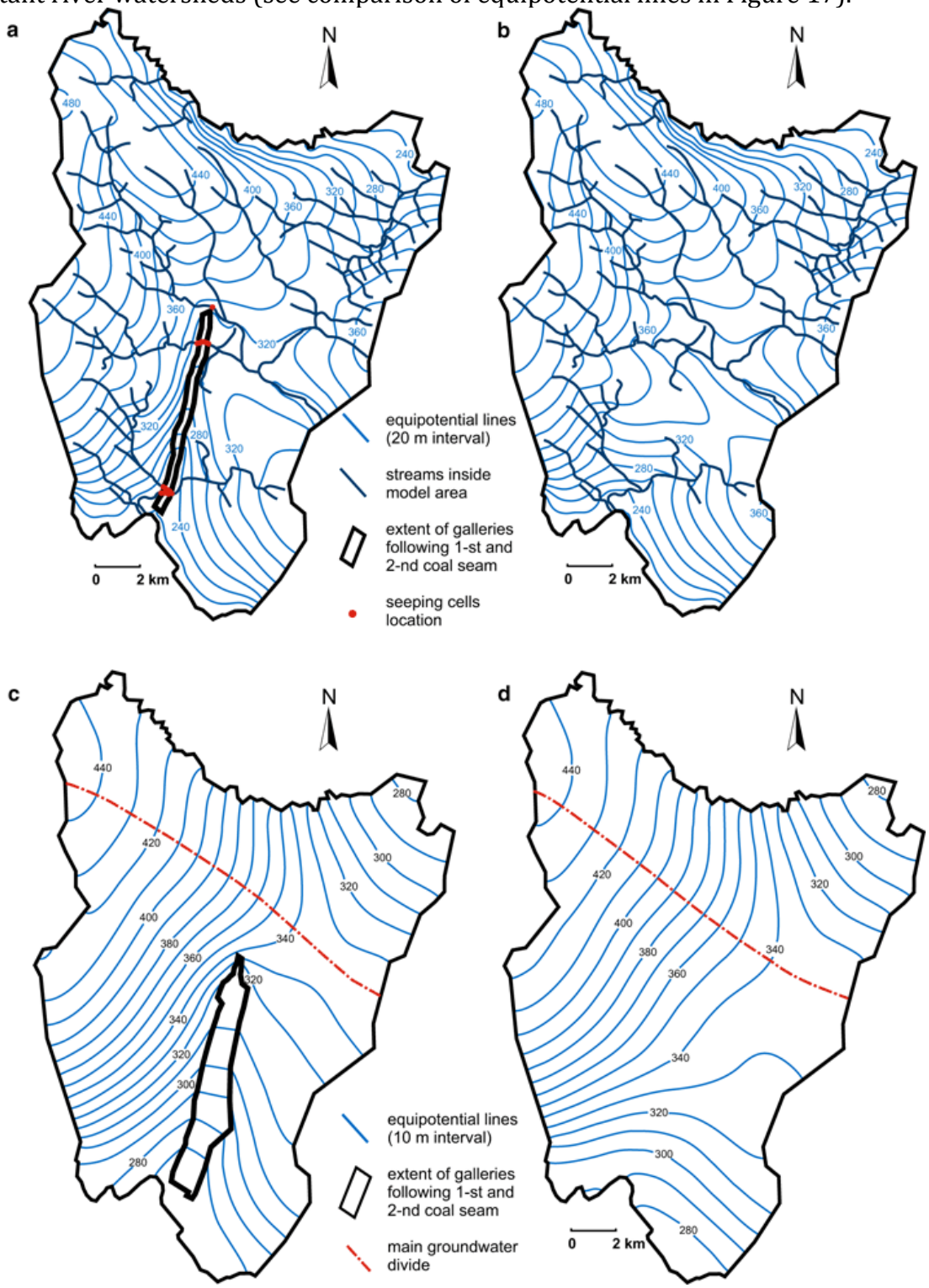


Figure 17: Equipotential lines in the 1st model layer representing local groundwater flow system in the current stage scenario (a) and the pre-mining stage scenario (b) and in the 10th model layer (depth 1400 m below surface) representing regional groundwater flow system in the current stage scenario (c) and (d) pre-mining stage scenario (P 5).

Numerical modelling remains the integrative tool: mining hydrogeology routinely couples layered/anisotropic property fields with stress-history–consistent boundary conditions to reproduce observed drawdown/rebound and to test management scenarios, including final flooding of the mines. Representative applications demonstrate how calibrated heterogeneous models reconcile stream-loss segments, fractured-mass storage, and discharge points during and after dewatering (Rapantová et al. 2007). It is crucial that research into the impact of existing or planned mining operations includes a comprehensive range of specific activities. These activities must include the monitoring of hydrogeological and geochemical parameters, as well as the development of specific methods for assessing the impact on water elements. The utilisation of groundwater flow modelling tools is a pivotal component in the forecasting of future mining and post-mining activities. For post-mining rebound, heterogeneity controls the sequence and rates at which compartments re-connect and pressurize. Extending monitoring networks into overlying aquifers and across barrier formations—paired heads, chemistry, and lithological logging—has become standard practice to detect vertical connectivity (von Kleinsorgen et al. 2021, Genth et al. 2024).

With the ongoing push for decarbonization, flooded deep mines are becoming a potentially significant source of geothermal energy (e.g., Burnside et al. 2016, Loredo et al. 2016, Bao and Liu 2019, Menéndez et al. 2019). Flooded deep mines may exhibit significant changes in mine water composition during mining operation, as firstly mentioned by Cairney and Frost (1975). Deep flooded mines were found to have marked depth stratification of mine water, which is observed in both ore and coal mines, as summarised in work of Mugova and Wolkersdorfer (2022). The upper layer is typically characterized by lower mineralization and temperature, while the lower layers have higher mineralization and contents of potentially environmentally hazardous components (Zeman et al. 2008). In a comprehensive study evaluating stratification in 29 deep mines (Mugova and Wolkersdorfer 2025), they conclude that the upper layer is actively involved in groundwater circulation and is hydrodynamically separated from the lower layers. The authors point to possible stratification disturbances due to anthropogenic interventions, which may typically include mine water pumping, sudden collapses of mine tunnels, but also the influence of the density of separated layers by a tracer test. Given the connection between the first stratified layer and the active circulation of groundwater, the issue of the connection between flooded mine workings and surface water and the predisposition of their hydraulic connection by natural or mining-induced faults will continue to be an actively investigated topic.

3 Groundwater contamination

Contamination of groundwater by volatile organic compounds (VOCs) is a widespread environmental problem that has prompted extensive research in both field and laboratory settings, with the objective of enhancing comprehension of their fate and behaviour. The concept of natural attenuation has emerged as a means to describe the suite of processes, including biodegradation, sorption, volatilisation, and dispersion, which have the capacity to naturally contain or remediate contaminated groundwater (Wiedemeier et al. 1996). Since the early 1980s, there has been a considerable expansion of knowledge regarding the transformation of VOCs in groundwater. This expansion has revealed that abiotic degradation generally proceeds at a much slower rate than that of microbially mediated reactions. Chlorinated hydrocarbons (CHCs) represent a significant category of anthropogenic contaminants frequently observed in groundwater at industrial sites. Among them, chlorinated ethenes - tetrachloroethene (PCE) and trichloroethene (TCE) were extensively utilised in dry cleaning and degreasing operations, as well as in numerous other applications (Doherty 2000a, Doherty 2000b, McCarty 2010). Chlorinated ethenes are among the most frequently detected contaminants in developed countries (Squillace et al. 1999). Their high density and viscosity permit migration to considerable depths (Pankow and Cherry, 1996), while their relatively high solubility and low sorption tendency facilitate the formation of long plumes that may reach surface water bodies (Schwarzenbach et al. 1983, Wiedemeier et al. 1999, Ellis and Rivett 2007). In the vicinity of rivers and lakes, abrupt geochemical changes in sediments have been shown to exert a significant influence on the behaviour of chlorinated ethenes (Lorah and Olsen, 1999, Chapman et al. 2007). The elevated oxidation state of the carbon atoms in highly chlorinated VOCs (e.g., TCE, PCE) results in the preferential degradation of these compounds via reductive rather than oxidative pathways under anaerobic conditions. The primary process is hydrogenolysis, in which chlorine atoms are successively replaced by hydrogen, yielding less-chlorinated and more reduced products (Vogel et al. 1987, Bouwer 1992).
Reductive dechlorination of PCE has been observed to occur under almost all redox conditions, with the exception of oxic aquifers. In contrast, TCE has been shown to require Fe(III)-reducing or stronger conditions for its reduction. Further dechlorination of cis-1,2-dichloroethene (cDCE) and vinyl chloride (VC) has been observed to occur exclusively under conditions conducive to sulphate reduction or methanogenesis (Vogel and McCarty 1985, Freedman and Gossett 1989, Maymo-Gatell et al. 1995, Rügge et al. 1999, Bradley 2000). Furthermore, transformation intermediates have been observed to undergo metabolic or co-metabolic oxidation under oxic or anoxic conditions (Wackett and Gibson 1988, Little et al. 1988, Davis and Carpenter 1990, Bradley and Chapelle 1998). It is imperative to differentiate between complete and partial transformation, given the high toxicity of VC. This is of particular importance when conducting risk assessments. TCE has been identified as the most prevalent groundwater contaminant in industrial settings, with numerous studies concentrating on its natural attenuation (Stroo et al. 2003, Wiedemeier et al. 1999, NRC 2000).

In the Czech Republic alone, remediation technologies for subsurface decontamination were carried out at 1,827 sites by the end of 2023 (Suchánek et al. 2024). Chlorinated solvents are the second most common group of contaminants at these sites, after petroleum hydrocarbons. In terms of remediation technology use, they are the group of contaminants that is most frequently remediated. Alongside conventional technologies

employing hydraulic methods, as well as aggressive physical and chemical methods, monitored natural attenuation (MNA) is a promising, low-cost technology that has been in use since the late 1990s. However, its applicability is significantly limited by the natural degradation processes of contaminants occurring at the sites. For example, between 2003 and 2023, MNA was only used at 13 sites contaminated by chlorinated solvents in the Czech Republic (Suchánek et al. 2024).

Natural attenuation of chlorinated solvents in groundwater has been the subject of intensive study for more than three decades. A consistent message across the literature is that the effectiveness of MNA is governed by redox zonation in aquifers and streambed sediments, which determines whether conditions are favourable for reductive dechlorination and whether complete shift to ethene is possible. Early laboratory microcosm studies initiated the foundational research that led to the subsequent understanding of natural attenuation of chlorinated ethenes. Vogel and McCarty (1985) first documented that PCE undergoes sequential reductive dechlorination to TCE, DCE isomers, VC, and ultimately to ethene under strictly methanogenic conditions, identifying VC as a particularly persistent intermediate that can inhibit natural attenuation (Vogel and McCarty 1985). Freedman and Gossett (1989) advanced this understanding by conducting ^{14}C tracer experiments, which demonstrated complete biological transformation of PCE and TCE to ethene in methanogenic systems when suitable electron donors (notably methanol) were supplied. Inhibition experiments confirmed the key role of methanogenic conditions in enabling reductive dechlorination (Freedman and Gossett 1989). These studies established methanogenic zones as critical environments for achieving complete dechlorination through natural processes. A significant paradigm shift occurred following the description by Maymó-Gatell et al. (1995) of an H_2-utilising enrichment culture that dechlorinated PCE completely to ethene in the absence of methanogenesis and acetogenesis. This provided the first clear evidence for specialized organohalide-respiring bacteria—later identified as Dehalococcoides mccartyi—capable of using chlorinated ethenes as terminal electron acceptors. The present study demonstrated that complete dechlorination is not merely a by-product of methanogenesis, but can occur wherever there are sufficiently reducing conditions and molecular hydrogen available. This finding thus serves to broaden the range of redox environments that are compatible with MNA (Maymó-Gatell et al. 1995).

Redox zonation soon emerged as the central control on natural attenuation in the field. As contaminant plumes migrate, the sequential consumption of electron acceptors typically produces a redox sequence. This sequence begins in oxic and nitrate-reducing conditions at the fringes of the plume and progresses to iron- and sulphate-reducing conditions, and finally methanogenic conditions in the plume core. Barrio-Lage et al. (1986) provided early experimental evidence that dechlorination only occurs under strictly anaerobic conditions. As stated by Rügge et al. (1999), field confirmation was provided through the execution of an anaerobic injection experiment in a landfill leachate plume at Grindsted, Denmark. The observation of degradation of chlorinated compounds was limited to anoxic plume segments, while persistence dominated under more oxidising conditions (Rügge et al. 1999).

In a complementary riverbank infiltration study, Schwarzenbach et al. (1983) demonstrated that the infiltration of river water into groundwater establishes pronounced redox gradients within riverbank sediments. These in turn control the behaviour of VOCs (Schwarzenbach et al. 1983). In order to diagnose dominant terminal electron-accepting processes (TEAPs) in situ, Lovley et al. (1994) introduced dissolved hydrogen as a sensitive geochemical indicator, defining characteristic dissolved hydrogen ranges for nitrate,

iron, and sulphate reduction and methanogenesis. This approach is still widely utilised for the delineation of redox zonation, and to evaluate the suitability of conditions for reductive dechlorination (Lovley et al. 1994). Interactions between groundwater and surface water have been shown to have a significant impact on redox environments, which in turn can influence chlorinated solvent plumes. Conant et al. (2004) investigated a PCE plume discharging to a river and found minimal degradation within the aquifer but extensive anaerobic biodegradation within the upper metres of the streambed, where c-1,2 DCE and VC accumulated prior to discharge. This evidence indicates that the streambed acts as a natural bioreactor (Conant et al. 2004). Chapman et al. (2007) conducted an examination of a TCE plume in proximity to a sandy river system and cautioned that sharp concentration decreases in the vicinity of surface water may be indicative of discharge and volatilisation, rather than biodegradation. The authors emphasised the necessity of evaluating redox conditions in hyporheic and near-stream zones when interpreting apparent attenuation (Chapman et al. 2007). In a city-scale context, Ellis and Rivett (2007) demonstrated that although anaerobic degradation products such as cis-DCE were prevalent in upgradient groundwater, which was predominantly oxic, the presence of coarse-grained riverbed sediments impeded further reductive dechlorination. This finding underscores the notion that surface-water sediments cannot be assumed to support effective MNA without demonstrated reducing conditions (Ellis and Rivett 2007).

A comparative study of sites with different redox zones (Kuchovský and Šráček, **P 6**) demonstrated the capacity for complete degradation of primary TCE to VC at sites where a shift to reducing conditions, including ferric iron reduction and sulfate reduction, is triggered by other contamination from organic compounds serving as electron donors for reductive dechlorination (e.g. petroleum hydrocarbons, organic matter from a waste landfill). In contrast, only negligible degradation of primary TCE has been observed at the site under aerobic conditions, resulting in the generation of a contaminant plume with a length exceeding 3000 metres. The intensity of natural attenuation processes fundamentally influences the maximum potential length of contamination plumes. While at the Zetor site it is only 64 m, at the Dubnica site, with comparable initial concentrations of primary TCE, it reaches up to 21800 m. These differences clearly demonstrate the importance of decay within the set of natural attenuation processes. The following figures show a comparison of the intensity of natural attenuation processes, with comparable source concentrations of TCE in contamination plumes. About 110 m downgradient from the redox interface (forming sulphate reduction conditions) only trace concentrations of chlorinated solvents were found at the Zetor site (Fig. 18). The total chlorinated solvents concentration was reduced from 2980 to 9 μg/L over this distance.

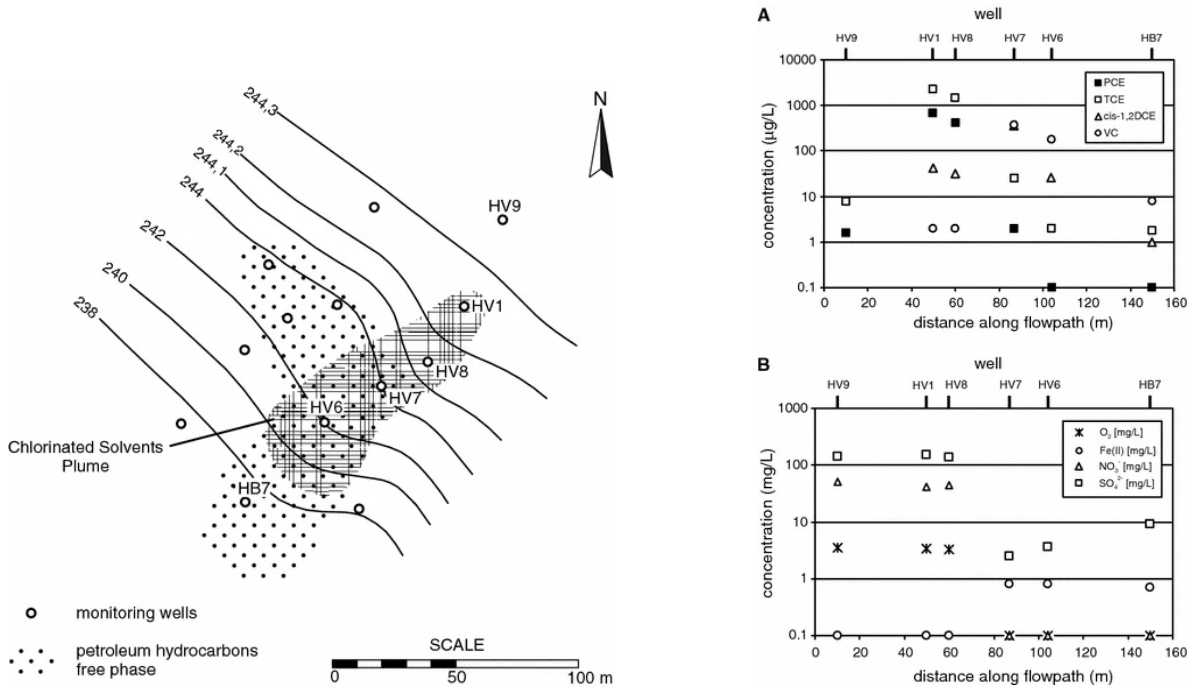


Figure 18: Zetor site setting (left) and changes in chlorinated ethenes concentrations (right, A) and redox-sensitive species (right, B) along flowpath (P 6).

At the Dubnica site, TCE contaminant plumes migrated to a distance of 3250 m, and further migration of the plumes was prevented only by the groundwater drainage into water extraction wells and the Vah River. Under documented aerobic conditions, TCE concentration decreased from 3320 to 129 µg/L (Fig. 19), with the decrease in concentration due to the process of hydrodynamic dispersion, while degradation rate was minimal.

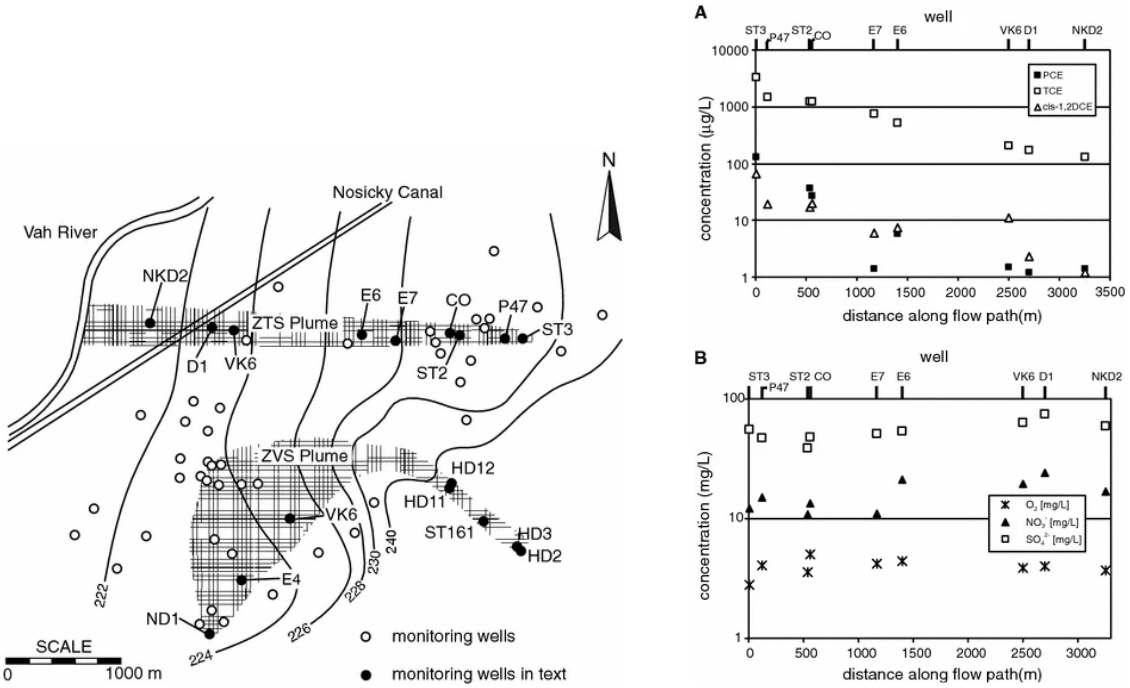


Figure 19: Dubnica site setting (left) and changes in chlorinated ethenes concentrations (right, A) and redox-sensitive species (right, B) along flowpath (P 6).

High-resolution studies of hyporheic zones emphasise the role of microscale redox variability in regulating attenuation pathways. Abe et al. (2009) combined compound-specific isotope analysis (CSIA), geochemistry, and microbial assays across a streambed transect. They demonstrated complete reductive dechlorination to ethene only where sulphate-reducing conditions and residence times ≥10 days prevailed. Concurrently, aerobic oxidation of VC occurred in microaerophilic niches (Abe et al. 2009). As demonstrated by Atashgahi et al. (2013), the presence or absence of oxygen gradients in surficial hyporheic sediments, measured in centimetres, determines whether the degradation of VC occurs via aerobic metabolic pathways or anaerobic co-metabolism. This explains the patchy distribution of VC attenuation in predominantly anoxic settings (Atashgahi et al. 2013). As Şimşir et al. (2017) further documented, streambed sediments receiving chlorinated-solvent discharge from fractured rock aquifers host dense populations of Dehalococcoides and Dehalobacter, and substantially reduce solvent fluxes to surface waters, confirming the role of the streambed as a natural bioreactor (Şimşir et al. 2017). These mechanistic and field insights have been consolidated into practical frameworks. In their 1999 study, Wiedemeier et al. proposed a comprehensive MNA paradigm, establishing a direct correlation between attenuation and quantifiable indicators of redox processes. This work also delineated the conventional decay constants and criteria for substantiating MNA as a remedial strategy (Wiedemeier et al., 1999). McCarty (2010) expanded upon this perspective, emphasising that sustained natural attenuation necessitates the long-term maintenance of sufficiently reducing conditions, which are typically characterised as sulfate-reducing to methanogenic. This process is supported by adequate electron-donor supply and favourable hydrogeological residence times (McCarty 2010).

The review of the extant literature indicates that while chlorinated solvents have been found to persist for decades in oxic or mildly reducing zones, complete detoxification to

ethene occurs reliably only within strongly reducing redox zones where specialized organohalide-respiring communities can thrive. In summary, natural attenuation of chlorinated ethenes is neither consistent nor assured. The success of this process is contingent upon the spatial and temporal distribution of redox zones, in addition to the presence of suitable microbial consortia and electron donors. Robust evaluation, therefore, necessitates more than concentration-trend analysis; it must encompass redox mapping (e.g. DO, ORP, redox-sensitive species, dissolved H_2), and, where possible, microbiological diagnostics. These tools enable differentiate between true biogeochemical attenuation and rather physical losses (dispersion, volatilization, sorption), thus determining whether MNA constitutes a defensible, sustainable remediation for a given chlorinated-solvent plume.

Kinetics of different orders are used to express the degradation rates; a significant amount of evidence demonstrates that chlorinated ethenes can be described by first-order decay kinetics. However, the reported degradation can vary by several orders of magnitude. This variability reflects differences not only between compounds, but also contrasts in hydrogeological settings, redox conditions and microbial communities. Following thermal source removal, Murray et al. (2019) demonstrated that PCE degraded with first-order rate constants in the range of 0,08–0,10 yr^{-1}, while cis-1,2 DCE exhibited much slower rates of 0,01–0,07 yr^{-1}. These results confirm that intrinsic biodegradation continues after aggressive source treatment, although the efficiency of natural attenuation depends strongly on the specific compound. A broader synthesis by Weatherill et al. (2018) reinforced this conclusion by compiling data from hyporheic zones, where groundwater–surface water exchange generates redox gradients that support both anaerobic and aerobic pathways. In such environments, PCE typically degraded at 1,1–3,7 yr^{-1} and TCE at 0,9–1,5 yr^{-1}, values that are significantly higher than those measured in many aquifers, highlighting the beneficial role of biogeochemical interfaces.

Laboratory experiments provide further evidence of how different pathways contribute to the overall first-order behavior observed in the field. Darlington et al. (2008) employed ^{14}C-labeled TCE in fractured sandstone microcosms, achieving a full mass balance of transformation products, including $^{14}CO_2$. The calculated apparent decay constant was approximately 0,3 yr^{-1}, a value that falls between typical field rates and those observed in organic-rich wetland sediments. Subsequent work by Darlington et al. (2013) demonstrated that cis-DCE can also undergo rapid abiotic transformation mediated by Fe(II) sulphide minerals, with rates as high as 8,7 yr^{-1}. These findings emphasize that both biotic and abiotic reactions can yield effective degradation, provided the mineralogical and geochemical conditions are favourable. Vinyl chloride, generally regarded as the most problematic intermediate because of its high toxicity and presumed persistence, can in fact degrade rapidly under aerobic conditions. Sing et al. (2004) described a highly enriched mixed culture capable of mineralizing vinyl chloride at rates of about 0,2 day^{-1} ($\sim$73 yr^{-1}), even when dissolved oxygen concentrations were as low as 1,8 mg L^{-1}. This study underscores the importance of local aerobic “hot spots” within predominantly anoxic aquifers, where first-order degradation can proceed at orders of magnitude faster than in the bulk aquifer matrix. In contrast, chlorinated ethanes such as 1,2-dichloroethane (1,2-DCA) are much more persistent. Rahim et al. (2022) monitored a shallow aquifer coupled with a reedbed system and reported a first-order constant of only 0,00372 yr^{-1}, equivalent to a half-life of roughly 186 years. Microcosm studies confirm that both aerobic and anaerobic degradation pathways are possible for 1,2-DCA, but Cruciata et al. (2024) demonstrated that rates depend heavily on site-specific microbial consortia and redox regimes. These results underline that 1,2-DCA represents a worst-case scenario for natural attenuation:

degradation is possible, but extremely slow without favourable microbial or geochemical conditions.

Historical case studies provide additional perspective. Chapelle and Bradley (1998) analysed plume concentration gradients at Kings Bay, Georgia, deriving first-order constants of approximately 0,01 day^{-1} for PCE and TCE and 0,025 day^{-1} for cis-1,2 DCE and VC. In contrast, Lorah and Olsen (1997) investigated a tidal wetland at Aberdeen Proving Ground, Maryland, and observed TCE degradation at much higher rates, 0,10–0,31 day^{-1} under methanogenic conditions and 0,045 day^{-1} under sulphate reduction. These values illustrate that aquifers rich in organic matter and sustaining reducing microbial processes can accelerate degradation by several orders of magnitude compared to sandy aquifers. Given such variability, quantitative models are indispensable for estimating site-specific decay constants and evaluating whether MNA can meet remedial objectives. BIOCHLOR, developed as a decision-support tool by the U.S. EPA, has become one of the most widely used screening models for this purpose. Clement et al. (2002) presented a case study demonstrating how BIOCHLOR can be calibrated to observed field concentrations, fitting sequential first-order decay constants along the PCE→TCE→DCE→VC→ethene chain and using the results to forecast plume behaviour and remediation timeframes. Such applications highlight the practical utility of first-order models: despite their simplicity, they can capture the essential trends in plume evolution and provide defensible inputs for decision-making. The framework has since been extended to integrate isotope data. Höhener (2016) introduced BIOCHLOR-ISO, which simulates stable carbon and chlorine isotope ratios in addition to concentrations. This innovation allows the model to exploit compound-specific isotope analysis (CSIA) to better constrain degradation pathways and reduce uncertainty in the calibrated constants. Building on this approach, Antelmi et al. (2021) applied BIOCHLOR-ISO at a chlorinated-solvent plume in Italy, coupling isotopic data with reactive transport modelling and using PEST optimization to calibrate site-specific decay constants. The calibrated model was then used to evaluate cleanup timeframes, showing that even modest differences in k can significantly change the predicted duration of remediation.

Applications of BIOCHLOR outside the isotope context also demonstrate its value. Kuchovsky and Sracek (**P 6**) applied the model across multiple contaminated sites in the Czech Republic, thereby highlighting the fact that the extent of the contaminant plume is controlled by the hydrogeological setting and redox conditions. The study made use of a range of locations which exhibited significantly different concentrations of primary contaminants, with these concentrations reaching up to the limits of their effective solubilities. The presentation of k values demonstrated that strongly reducing environments produces much more effective attenuation than oxic, thereby reinforcing the importance of geochemical context when interpreting MNA site potential. Determined first-order decay constants in the context of other studies are summarized in Table 1.

Table 1: Summary of chlorinated ethenes first-order decay constants

Compound	k (year^{-1})	Source	Environment
PCE	0,08	Murray et al. 2019 (field, post-thermal)	Field GW plume (post-thermal)
PCE	0,1	Murray et al. 2019 (field, post-thermal)	Field GW plume (post-thermal)
PCE	1,1	Weatherill et al. 2018 (review, hyporheic)	Review (hyporheic zones)
PCE	3,7	Weatherill et al. 2018 (review, hyporheic)	Review (hyporheic zones)
PCE	0,91	Kuchovsky and Sracek, **P 6** (field, landfill)	Field GW plume (Fe(III) reducing)
PCE	9,86	Kuchovsky and Sracek, **P 6** (field, LNAPL site)	Field GW plume (sulphate reducing)
PCE	0,4	Kuchovsky and Sracek, **P 6** (field, aerobic site)	Field GW plume (aerobic)
TCE	0,3	Darlington et al. 2008 (14C microcosm)	Lab microcosm (fractured sandstone)
TCE	0,9	Weatherill et al. 2018 (review, hyporheic)	Review (hyporheic zones)
TCE	1,5	Weatherill et al. 2018 (review, hyporheic)	Review (hyporheic zones)
TCE	3,65	Chapelle and Bradley 1998 (field)	Field (Kings Bay, GA)
TCE	36,5	Lorah and Olsen 1997 (wetland, methanogenic)	Wetland sediments (methanogenic)
TCE	113,15	Lorah and Olsen 1997 (wetland, methanogenic)	Wetland sediments (methanogenic)
TCE	1,5	Kuchovsky and Sracek, **P 6** (field, landfill)	Field GW plume (Fe(III) reducing)
TCE	6,76	Kuchovsky and Sracek, **P 6** (field, LNAPL site)	Field GW plume (sulphate reducing)
TCE	0,1	Kuchovsky and Sracek, **P 6** (field, aerobic site)	Field GW plume (aerobic, high DO)
cis-DCE	0,01	Murray et al. 2019 (field, post-thermal)	Field GW plume (post-thermal)
cis-DCE	0,07	Murray et al. 2019 (field, post-thermal)	Field GW plume (post-thermal)
cis-DCE	1	Darlington et al. 2013 (abiotic)	Lab microcosm (FeS-mediated)
cis-DCE	8,7	Darlington et al. 2013 (abiotic)	Lab microcosm (FeS-mediated)
cis-DCE	0,37	Kuchovsky and Sracek, **P 6** (field, landfill)	Field GW plume (Fe(III) reducing)
cis-DCE	2,92	Kuchovsky and Sracek, **P 6** (field, LNAPL site)	Field GW plume (sulphate reducing)
cis-DCE	5,99	Kuchovsky and Sracek, **P 6** (field, aerobic site)	Field GW plume (aerobic, high DO)
VC	9,125	Chapelle and Bradley 1998 (field)	Field (Kings Bay, GA)
VC	73	Sing et al. 2004 (aerobic culture)	Lab culture (aerobic, low DO)
VC	3,65	Kuchovsky and Sracek, **P 6** (field, landfill)	Field GW plume (Fe(III) reducing)
VC	1,83	Kuchovsky and Sracek, **P 6** (field, LNAPL site)	Field GW plume (sulphate reducing)
1,2-DCA	0,00372	Rahim et al. 2022 (field)	Field (shallow GW; reedbed site)

The high variability of the derived rate constants is reflected in the contrasting lengths of the steady-state contamination plumes, regardless of the initial concentrations of the primary contaminants. Hausman and Rifai (2005) utilised BIOCHLOR at a dry-cleaner site to establish a correlation between first-order constants and anticipated remediation timelines. Their findings demonstrated that minor variations in k resulted in substantial discrepancies in the predicted cleanup horizon, underscoring the necessity to explicitly consider source persistence in conjunction with biodegradation. Overall, the literature confirms that first-order decay constants for chlorinated ethenes and ethanes span from less than 10^{-3} yr^{-1} for compounds such as 1,2-DCA to more than 10^{2} yr^{-1} for vinyl chloride under aerobic "hot spot" conditions. This extraordinary variability makes it clear that site-specific assessment is indispensable. BIOCHLOR, particularly in its isotope-enhanced

form, provides a transparent and reproducible framework for deriving local decay constants from monitoring data, cross-checking them with isotopic and mechanistic evidence, and propagating the results into forecasts of plume longevity and remediation timeframes. For practitioners and regulators, this combination of empirical field data and calibrated modelling offers the most defensible basis for determining whether MNA is a viable remediation strategy at a given site.

4 Thermal water extraction

Geothermal energy, a form of renewable energy, is gaining popularity among many EU countries. The presence of thermal water requires favourable geological setting and hydrogeological conditions, which enable both forming and extraction of thermal water. Since the zones with elevated geothermal gradients are rare in thick continental crust regions, the importance of platform and molasse sediments buried into significant depths in zones with average or slightly higher geothermal gradients. The aquifers in Mesozoic sediments are among the most important geothermal energy reservoirs due to their increased permeability and large extent. However, the geological complexity of these systems, particularly the fractured and karstified carbonate formations, introduces significant uncertainty and heightens the likelihood of technical and environmental hazards. These aquifers also serve as vital resources for spa facilities, meaning that unsustainable abstraction can lead to conflicts of interest between energy developers and balneological users.

In the South German Molasse Basin, which is one of the most important geothermal energy reservoirs in Central Europe due to its high productivity and presence beneath almost the whole Molasse Basin, the Upper Jurassic (Malm) carbonate aquifer represents one of the most important geothermal reservoirs. The Malm aquifer is located between 1,500 and 5,500 m below ground surface and is covered by thick Tertiary sediments of the Molasse Basin (Mayrhofer et al. 2014; Homuth et al. 2015). Typical production rates of the geothermal wells in the Malm aquifer range from 30 to 150 L/s and the production temperatures reach up to 160 °C (Mayrhofer et al. 2014; Dussel et al. 2016). Numerical simulations demonstrate that its heterogeneous fracture and karst network enhances well productivity but simultaneously accelerates undesirable cooling and thermal breakthrough. Tzoufka et al. (2024) showed that density-driven buoyancy effects can partly be managed, yet uneven flow paths remain a major concern. Schintgen and Moeck (2021) added that variability in permeability and gravitational circulation governs the behaviour of thermal plumes, creating unpredictable patterns of heat transport. Both studies conclude that without careful balancing of extraction and reinjection, large-scale geothermal operations in Malm carbonates risk cooling the reservoir, lowering hydraulic heads, and ultimately reducing the discharge of thermal springs. Comparable challenges have been identified in the North German Basin, where Mesozoic sandstones and carbonates are identified as promising reservoirs. Frick et al. (2022) emphasized that the lack of geological data introduces a high level of uncertainty into capacity estimates. Such discrepancies can result in the overestimation of sustainable yields, which, in turn, can lead to long-term depletion. This risk is especially pronounced in areas where the same aquifers support spa resorts, which require stable temperatures and reliable flows. Beyond these regional case studies, broader European analyses provide further evidence of similar conclusions. Fleuchaus et al. (2020) conducted a comprehensive risk assessment of high-temperature ATES (HT-ATES) systems, identifying multiple hazards: carbonate scaling, corrosion of wells, groundwater contamination through improper reinjection, thermal breakthrough causing premature cooling, and even land subsidence linked to hydraulic imbalance. It is proposed that these threats are not universal but depend strongly on site-specific geology, aquifer mineralogy, and system design. The necessity for localized risk assessments and robust regulation is therefore highlighted.

German pilot projects further illustrate these vulnerabilities. Stemmle et al. (2022, 2025) demonstrated that ATES in fractured and carbonate aquifers can deteriorate groundwater quality, interfere with existing abstractions, and alter ecosystems when thermal plumes intersect sensitive habitats. They caution that monitoring and environmental impact assessment remain underdeveloped compared with the scale of deployment, increasing the likelihood of conflicts with spa operations, particularly in regions with a long cultural and economic reliance on thermal waters. Evidence from outside Germany paints a similar picture. A Norwegian review tailored to Polish conditions by Midttømme et al. (2017) likewise stressed that neglecting local geology increases the likelihood of recharge failure, clogging, and thermal imbalance—risks equally relevant for carbonate systems. More recent work from the Netherlands and Belgium (Scholliers et al. 2024) identified carbonate scaling, mineral interactions, and asymmetric plume migration as key challenges for sustainable HT-ATES integration into district heating networks. Similarly, Bloemendal et al. (2014, 2015) combined climatic and geohydrological assessments to demonstrate that fractured and karstified aquifers offer both high potential and high risk: their transmissivity allows substantial storage, but heterogeneity and preferential pathways amplify the chance of overexploitation and short-circuiting.
Taken together, these studies converge on a clear conclusion. Carbonate and Mesozoic aquifers provide considerable geothermal opportunities, but their geological complexity magnifies the risks of overuse, thermal instability, and conflict with spa water resources. Sustainable development requires more than technical optimization; it demands comprehensive site characterization, carefully designed well doublets, balanced extraction and reinjection strategies, long-term monitoring, and strict governance. Without such measures, the pursuit of renewable energy could unintentionally endanger thermal groundwater resources that have served European societies for centuries.

Across Central European sedimentary basins, hydrogeological modelling has proved decisive for understanding—and managing—the thermal-water systems hosted in Mesozoic carbonates. In Bavaria's South German Molasse Basin, three-dimensional and section-based simulations in the Malm (Upper Jurassic) aquifer clarified how permeability architecture and gravity-driven flow govern the thermal field and thus the siting and sustainable operation of doublets in the Munich region. A basin-scale, coupled flow–heat-transport model reproduced the distribution of temperature anomalies and showed that both conduction and advection must be resolved to de-risk exploration; the work linked pronounced cold/warm anomalies to structural and hydraulic controls rather than to surface boundary conditions alone (Przybycin et al. 2017). Focused two-dimensional thermal–hydraulic modelling across the Wasserburg Trough further demonstrated that contrasting Malm permeability end-members lead to distinct regimes, with forced convection by gravity-driven groundwater flow dominating over paleoclimate effects; this result constrains where high-productivity zones are likely and where conductive cooling prevails (Schintgen and Moeck 2021). At the field scale, a three-dimensional structural–hydrogeological model for Munich quantified sustainable abstraction scenarios and informed long-term use forecasts in the Upper Jurassic carbonates—explicitly linking reservoir architecture to producible thermal-water volumes (Dussel et al. 2016). Complementary thermofacies-guided reservoir characterization of Malm carbonates tightened priors on petrophysical parameters used in models and highlighted the role of facies-controlled heterogeneity for flow and heat transport (Homuth et al. 2015). In the Paris Basin Dogger (Middle Jurassic) carbonates, decades of operation enabled model calibration against long production histories. Layered reservoir models at the doublet scale were

used early to assess thermal-breakthrough sensitivity to vertical heterogeneity and to evaluate interference between injection-cooled zones and producers—directly informing well spacing and reinjection strategies (Le Brun et al. 2011). More recently, a calibrated Dogger model assimilating roughly forty years of production data showed that reproducing observed temperatures and pressures requires accounting for regional lateral cross-flow and for variations in deep heat flux; the study achieved ≤1.5 °C misfits and used the calibrated state to map cooler zones created by long-term operations, with clear implications for doublet placement and lifetime (Renaud et al. 2024). At the system-planning scale, techno-economic analyses coupled to reservoir simulations demonstrated how well spacing controls both thermal interference and net present value; in heterogeneous hot-sedimentary aquifers, optimized spacing can maintain production temperature while improving field economics (Willems et al. 2017). Against this operational backdrop, basin syntheses emphasized how the Dogger's productive oolitic and dolomitic layers support large district-heating capacity when managed with reinjection—insight that emerged from iterative cycles of modelling and monitoring (Lopez et al. 2010). Triassic carbonates provide parallel lessons where urban subsurface use and storage are priorities. In Berlin's Muschelkalk, an integrated hydrogeochemical–microbial investigation combined with geochemical simulations quantified risks of mineral disequilibria during prospective high-temperature aquifer thermal energy storage operation, including spatial–temporal patterns of calcite dissolution/precipitation under cyclic charging and discharging. These reactive-transport results delineate operating envelopes that limit formation damage and maintain injectivity (Virchow et al. 2024). Regionally, thermal-field models around Berlin have long shown that structural configuration and basin hydraulics imprint strong lateral temperature variations—boundary conditions that any local project must reflect in its performance forecasts (Sippel et al. 2013).

The pivotal study of Chroustová et al. (**P 7**) expanded through the research of Pasternakova et al. (2025) in the region utilized long-term sampling in two balneological boreholes (Czech MUS-3G and Austrian Laa Th N1) and archival data from oil and natural gas prospection boreholes to delineate recharge and discharge zones, temperatures and renewable volume of groundwater in the deep Jurassic aquifer. The site location is in Fig. 20. The area is currently used only for balneological purposes, but the structure is promising for advancing balneological use and as a geothermal energy resource.

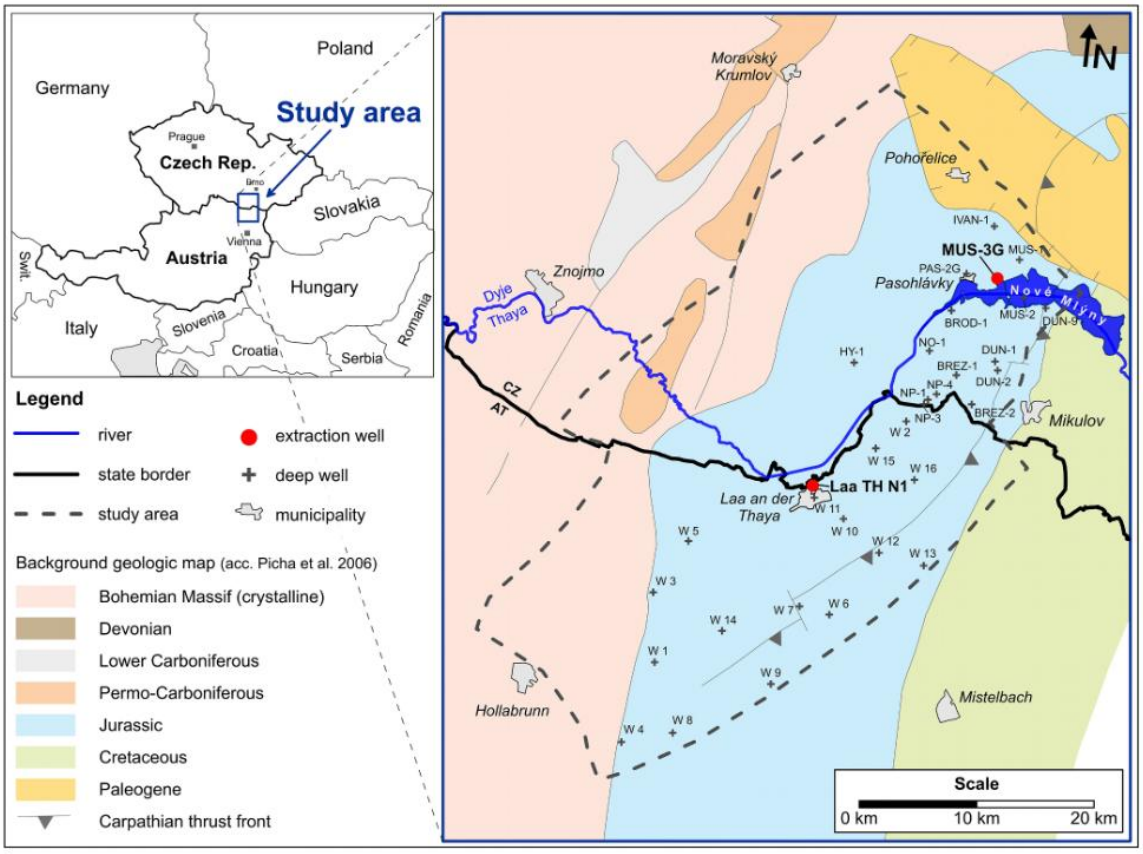


Figure 20: Location of the site with position of the extraction wells MUS-3 G and Laa TH N1 and other archive deep wells reaching the Jurassic aquifer (P 7).

The thermal water structure is on a regional scale formed by one aquifer. However, it is composed of different units: weathered and fractured tops of the crystalline basement of Bohemian Massif, the Jurassic sequence representing the main reservoir rocks with the Dogger sediments and Malm deposits of the Altenmarkt Group and the Kurdejov Limestones, and permeable basal clastic of Miocene deposits of the Egerian and Eggenburgian. The carbonates of the autochthonous Malm offer suitable conditions for thermal water use, of which karstified limestone, coral reef limestone, and dolomite have the best reservoir capacity and is already being used for balneological purposes by the spa resorts in Laa and Pasohlávky. Due to the highest transmissivity of the Jurassic Dogger and Malm sediments in comparison to other units, the aquifer is named as Jurassic aquifer. The top and the bottom of the aquifer are at a depth from 160 to -3000 m a.s.l. and from 110 to -4400 m a.s.l, respectively. The Jurassic aquifer is sloping in SE direction, the Musov transition zone divides the structure in NW and SE parts (Fig. 21).

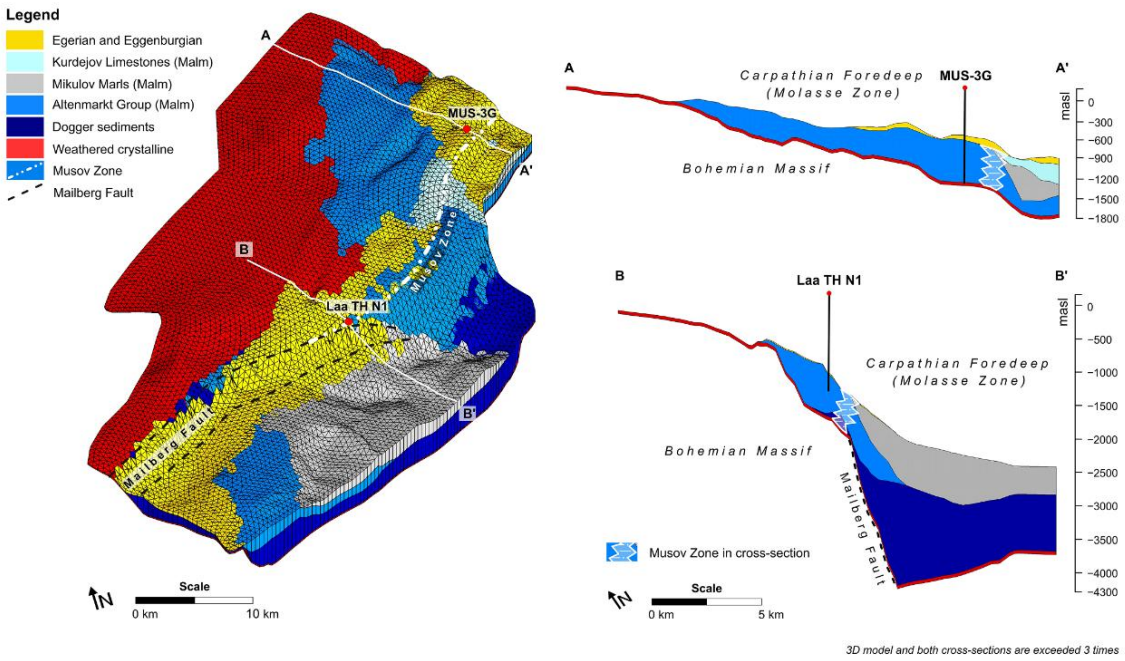


Figure 21: 3D geological model of the aquifer with cross-sections of the NW-SE direction (Pasternakova et al. 2025).

The shallower NW section is characterized by water with lower total mineralisation ranging from 0.4 to 15 g/L (see Fig. 22), the deeper SE section contains water with significantly higher TDS values varying from 15 to 56 g/L. The spatial distribution of TDS further designates that the low salinity groundwater is found at the NW boundary of the aquifer, formed mainly by the weathered zone of the Bohemian Massif and Altenmarkt Group. The TDS values are increasing towards the Musov Zone and Mailberg Fault, according to groundwater flow. The high TDS values are resulting from long residence time associated with an enhanced water-rock interaction, typical for a close hydrogeological structure with limited connection to groundwater flow.

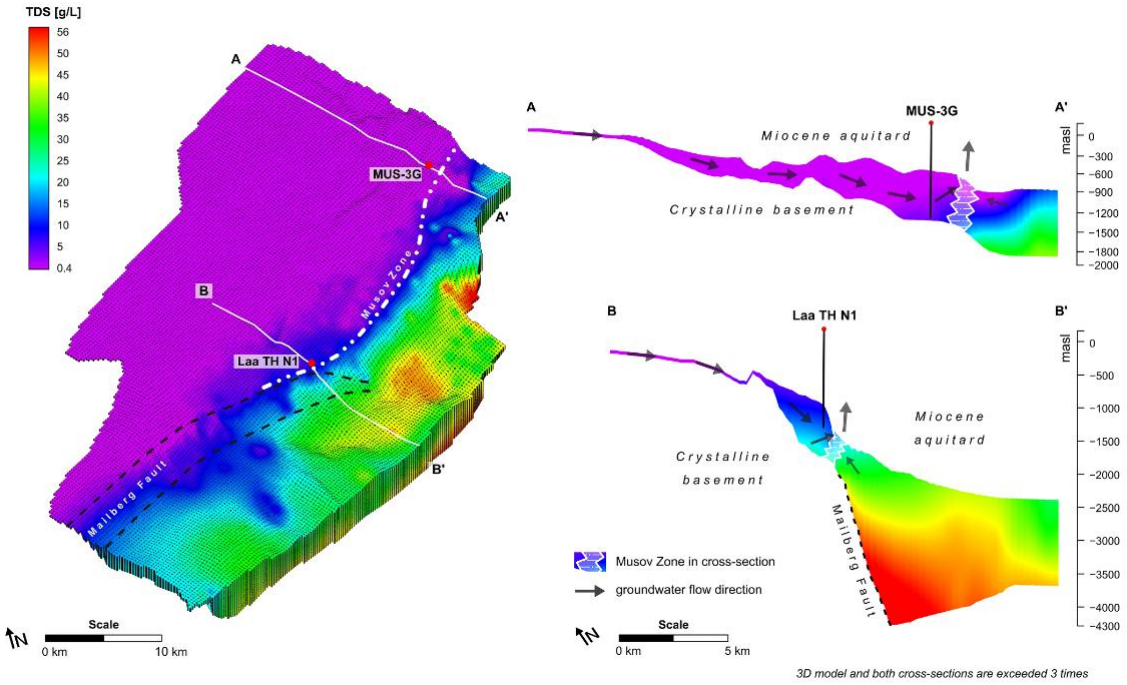


Figure 22: A 3D model of the spatial distribution of TDS in the aquifer with two cross-sections of the NW—SE direction.

The observed groundwater temperature ranges from 37 °C to 110 °C with the highest values found in the deepest part of the SE aquifer section, mostly on the Austrian side. The mean value of the calculated geothermal gradient reaches 28,5 °C/km. Originally marinogenic waters in the northwestern section are strongly affected and degraded by the infiltration of fresh meteoric waters. The interpretations based on hydrochemistry were confirmed by cation geothermometry. According to the Na–K–Mg diagram, most of the samples from both aquifer sections are mature waters at partial equilibrium with reservoir rocks (Fig. 23). The immature waters are only found in the NW, where it indicates the occurrence of processes like re-equilibrium (or unattained full equilibrium) and dilution by shallow cold waters of meteoric origin. In addition, the geothermometry estimations indicate a potential inflow of warmer groundwaters from greater depths into both aquifer sections.

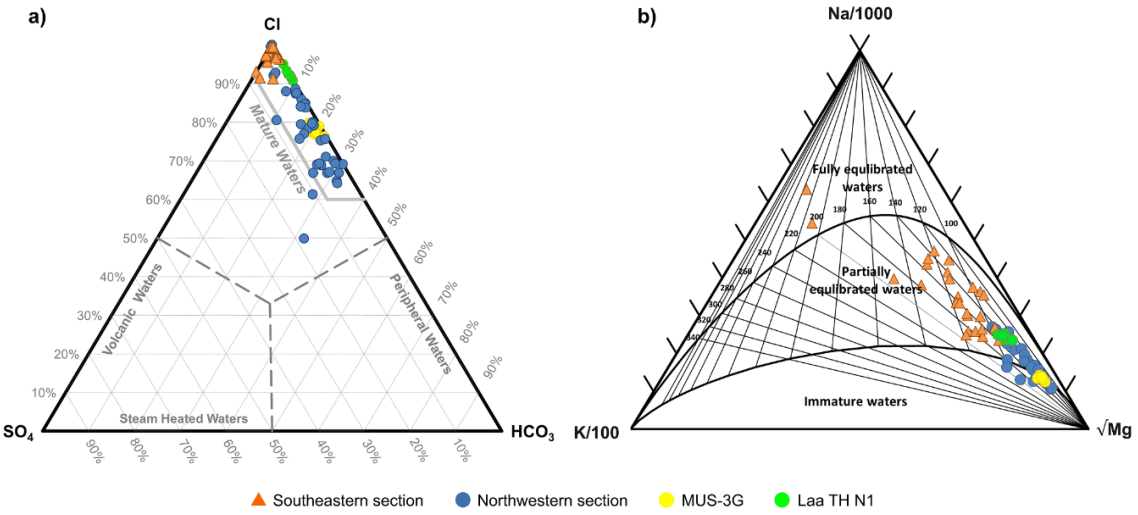


Figure 23: The Cl–SO_4–HCO^3 and Na–K–Mg ternary diagrams with plotted groundwater samples from the studied aquifer (Pasternakova et al. 2025).

Cross-border modelling of the deep Jurassic aquifer in the South Moravia (Czech Republic) and Lower Austria illustrates how fully coupled groundwater-flow and variable-density/viscosity transport modelling (implemented with MODFLOW-2000/MT3DMS coupled in SEAWAT) can quantify both flow directions and discharge magnitudes from several-kilometre-deep carbonate reservoirs. The study shows relatively high flux of 350 L/s in the Jurassic aquifer, with inflow from both NE and SE directions (see Fig. 24). The calibrated three-dimensional model reproduced upward discharge into the Dyje/Thaya River via the Mušov Zone and matched observed chloride mass fluxes, constraining regional flow and confirming an ~80–85 L s^{-1} discharge that materially contributes to river chloride load (**P 7**). The recharge zone has been identified in the outcrops of the Bohemian Massif.

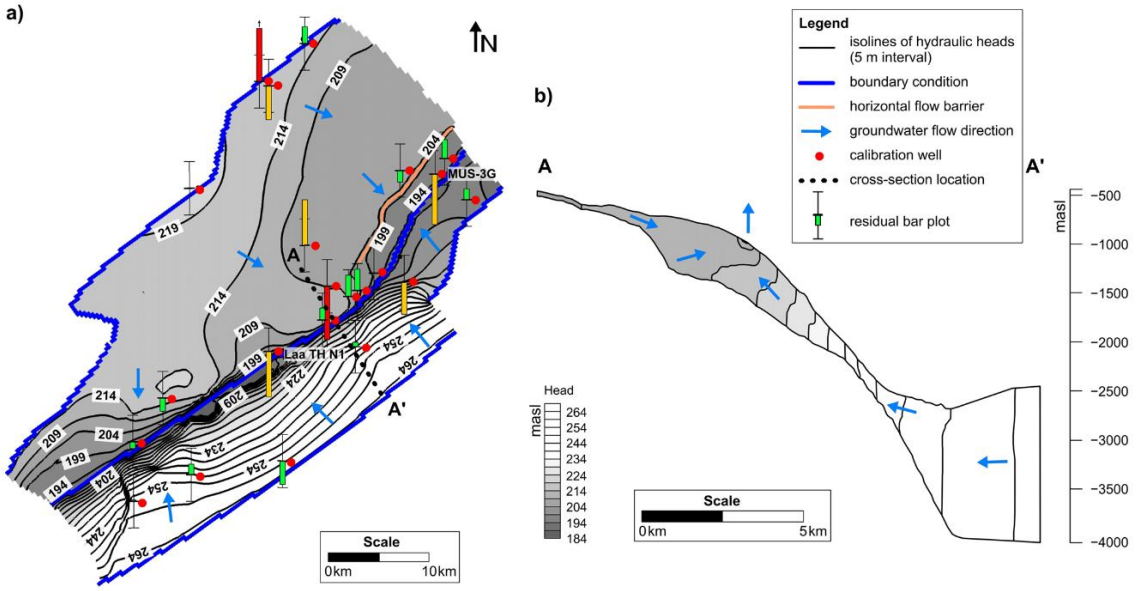


Figure 24: Spatial distribution of the simulated hydraulic heads in the 3-D numerical model at the top layer (a) and the cross-section A-A' with equipotential lines and principal flow directions (b). Coloured bars represent the range of residual error (green<2 m, yellow>2 m, red>4 m) (P 7).

Together, the studies by Chroustová et al. (**P 7**) and Pasternáková et al. (2025) show why modern hydrogeological modelling is not merely descriptive: it quantifies recoverable heat and water, resolves deep heat-flux and cross-flow controls needed to match history, and delineates sustainable operating windows—rates, reinjection temperatures, and spacing—that minimize thermal interference and chemical risks (Harbaugh et al. 2000; Lopez et al. 2010; Renaud et al. 2024).

5 Conclusion

The area between the Czech Massif and the Western Carpathians is a unique region where the typical examples of impact of anthropogenic activity on groundwater are observed. Even with the use of modern technologies and efforts to manage natural resources sustainably, anthropogenic activity can be expected to continue to affect groundwaters. This impact is often related to the spatial coexistence of geological formations where significant groundwater resources and raw material deposits are located. The impact on groundwater is quite evident in the example of sand and gravel extraction in open pits. However, it should be noted that the impact is rather local, limited to the close vicinity of the open pits; no regional impact on the water table has been observed. The most serious negative impact is the result of direct evaporation from open water surfaces; the pits are filled with groundwater, and any negative balance of the groundwater body in the open pit is replenished by increased groundwater seepage from the surrounding aquifer. In the case of predicted climate change scenarios, the increasing evaporation may lead to a reduction in natural groundwater resources in aquifers important for groundwater supply. The assessment of the impact of flooded deep mine workings on groundwater must be considered in the context of all water features in the landscape. The hydraulic connection of mine workings with shallow overburden aquifers and, where applicable, with surface watercourses is a common phenomenon in rocks where the mining-affected rock environment has the characteristics of a hydrogeological massif. Groundwater flow is significantly influenced by natural and mining-induced fault zones. These can result in the complete loss of surface water flow and, conversely, unexpectedly high mine water outflows. The hydrogeological conditions in the vicinity of deep abandoned flooded mines should be understood as new natural conditions formed by historical anthropogenic activity. The new conditions must be considered in view of the permanent impact of flooded mine workings on groundwater and surface water. In such areas, water management planning must respect these new conditions and adapt activities related to the use of groundwater and surface water (e.g., designing the locations of extraction wells, projects requiring a concept of minimum required flows in surface streams, use of geothermal energy). A suitable tool for assessing the impact of mining on groundwater, particularly from a water balance perspective, is 3-D numerical modelling of groundwater flow. This can typically be used to clarify the ongoing processes of mine water formation. When changing the parameters characterizing geological features or climatic characteristics based on verified or highly probable scenarios, it is also appropriate to use it for predictive assessment of future impacts or to determine the causes of currently observed phenomena based on comparison with historical scenarios.

Environmental pollution caused contaminants of anthropogenic origin, assessed using the example of chlorinated ethylenes, demonstrates the need for detailed evaluation of hydrochemical parameters at the sites. The intensity of degradation by the reductive dechlorination process is highly variable and significantly affects the possible steady-state lengths of contamination plumes migrating in aquifers. However, under suitable conditions, degradation processes can effectively remove even concentrations approaching the values of effective solubility, indicating the likely presence of DNAPL's liquid phase in sources of contamination. Natural attenuation processes can thus fully replace costly and time-consuming remediation methods.

Jurassic platform sediments of the Czech Massif buried under the sedimentary fill of the Carpathian foredeep at the Czech-Austrian border represent a promising structure in terms of geothermal energy use. Its use, as in cases of analogous geological structures, requires specific hydrogeological evaluation of the structure, including advanced numerical 3-D modelling of groundwater flow including the density-driven flow packages and detailed evaluation of hydrochemical parameters. Advanced research methods can contribute to understanding the processes of thermal water formation and assessing the renewability of thermal waters, which must be a step preceding proposal for their economical use.

A lack of understanding of the processes occurring as a result of the above-mentioned examples of anthropogenic impact on groundwater can lead to significant economic losses and negative impacts on the whole of society.

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6.1 Author´s publications

[P1][1] VANICEK, Petr, Adam RICKA, Tomas **KUCHOVSKY**, Bibiana PASTERNAKOVA, Katerina CHROUSTOVA a Karel SUHAJDA. Sustainable groundwater resource extraction influenced by changing climate and pit lake expansion in East Bohemia, Czech Republic. *Journal Of Hydrology-Regional Studies* [online]. 2025, **59**(102400, Article 102400). ISSN 2214-5818. doi:10.1016/j.ejrh.2025.102400

Scientific work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
25	30	25	25

[P2] **KUCHOVSKY**, Tomas, Adam ŘÍČKA a Jaroslava ČERVENKOVÁ.Impact of Gravel Pits on Ground water: Case study of Gravel Pits near the Mohelnice City, Czech Republic. In Mine Water and the Environment PROCEEDINGS, 10th International Mine Water Association Congress, June 2-5. 2008, Karlovy Vary, Czech Republic. Ostrava: VŠB - Technical University of Ostrava. 2008, 69 - 72, ISBN 978-80-248-1767-5.

Scientific work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
75	0	90	100

[P3] **KUCHOVSKY**, Tomas, David GRYCZ a Michala DRÁBOVÁ. Regional Impact of Mining on Stream Drainage Characteristics in the Rosice - Oslavany Coal Mining District, Czech Republic. In Mine Water and the Environment PROCEEDINGS, 10th International Mine Water Association Congress, June 2-5. 2008, Karlovy Vary, Czech Republic. Ostrava: VŠB - Technical University of Ostrava. 2008, 155 - 158, ISBN 978-80-248-1767-5.

Scientific work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
80	0	90	100

[P4] RICKA, Adam, Tomas **KUCHOVSKY**, Ondra SRACEK a Josef ZEMAN. Determination of potential mine water discharge zones in crystalline rocks at Rozna, Czech Republic. *Environmental Earth Sciences* [online]. 2010, **60**(6), 1201–1213. ISSN 1866-6299. doi:10.1007/s12665-009-0261-8

Scientific work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
40	20	30	30

[P5] **KUCHOVSKY**, Tomas, Adam RICKA a David GRYCZ. Using Numerical Modeling to Understand the Discharge from a Flooded Abandoned Underground Mine. *Mine Water And The Environment* [online]. 2017, **36**(4), 606–616. ISSN 1616-1068. doi:10.1007/s10230-017-0455-3

Scientific work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
80	0	90	100

[P6] **KUCHOVSKY**, Tomas a Ondra SRACEK. Natural attenuation of chlorinated solvents: a comparative study. *Environmental Geology* [online]. 2007, **53**(1), 147–157. ISSN 0943-0105. doi:10.1007/s00254-006-0628-z

Scientific work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
90	0	80	80

[P7] CHROUSTOVA, Katerina, Adam RICKA, Bibiana PASTERNAKOVA, Tomas **KUCHOVSKY**, Thomas R. RUDE a Josef ZEMAN. Identification of deep Czech Republic-Austria transboundary aquifer discharge and associated river chloride loading. Environmental Earth Sciences [online]. 2024, 83(12, Article 366). ISSN 1866-6299. doi:10.1007/s12665-024-11670-7

Scientific work (%)	Supervision (%)	Manuscript (%)	Research direction (%)
25	30	25	25

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7 List of papers