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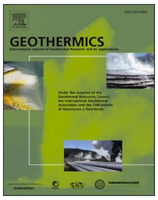

Injection related issues of a doublet system in a sandstone aquifer - A generalized concept to understand and avoid problem sources in geothermal systems

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ABSTRACT

This study proposes a concept and presents a workflow to examine potential reasons for low injectivity of sandstone aquifers. Injection related problems are a major challenge for the sustainable utilization of geothermal waters. In order to completely understand and avoid the geothermal reinjection problems, potential problem sources acting on different scales should be taken into consideration. Thus, in the workflow, possible problem sources are considered on regional, reservoir and local scale and categorized into 1) effect of regional hydraulics (potential presence of overpressure and upward flow) 2) inadequate reservoir performance (limited extent, low permeability and performance) and 3) local clogging processes (particle migration, mineral precipitation, microbial activity). Hydraulic conditions are characterized by defining the pressure regime and the direction of vertical driving forces. The reservoir properties are given by determining the grain size and the size of the reservoir layers, as well as the permeability and the transmissivity of the reservoir and the capacity of the injector. Physical, chemical, and biological clogging processes are investigated by specifying the rock properties and determining particle content of the fluid; by analysing the type, probability and amount of the scaling and estimating the potential for corrosion; and by evaluating the possibility of biofilm formation. The concept and the workflow were first tested on a geothermal site (Mezőberény, SE Hungary, installed in 2012) that had to stop operation because of unsuccessful reinjection. The low injectivity of the well is a consequence of several separate problems and their interaction: Reservoir properties are insufficient due to low permeability and transmissivity of the reservoir and the limited vertical and horizontal extension of the sandstone bodies. Precipitation of carbonates, iron and manganese minerals is predicted in hydrogeochemical models and observed in solid phase analysis. Microbial material is produced from the particularly high organic content of the produced thermal water. Injection problems due to hydraulic effects are not expected since the regional pressure regime is slightly subhydrostatic. In summary, reservoir properties determine a low injectivity, which is further decreased to a critical level by the clogging processes. The proposed generalized concept guides a detailed reservoir and geothermal system analysis which is essential for a sustainable geothermal operation.

1. Introduction and objectives

Reinjection of cooled geothermal brines into porous reservoirs can ensure pressure stabilization of reservoirs in order to avoid pressure decline and to mitigate subsidence (Gringarten, 1978; Axelsson, 2012). In most geothermal projects, reinjection is mandatory due to negative impacts of surface discharge as an alternative to dispose the produced water. Negative consequences of surface discharge would be reservoir depletion, thermal or chemical pollution of rivers or lakes and contamination of the atmosphere by e.g. methane, hydrogen sulphide or carbon-dioxide (Axelsson, 2012).

The injection technology of oil industry with high pressure injection is often unsustainable and uneconomical for geothermal systems in the long-term because of the high pumping costs required to generate the extra injection pressure (Szanyi et al., 2014). Therefore, the successful geothermal reinjection is not straightforward. In case of porous

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sandstone geothermal reservoirs, difficulties originating from physical-chemical or geological processes have been experienced worldwide (Stefansson, 1997). These processes can strongly hinder the reinjection process and decrease its capacity (Ungemach, 2003).

Though individual processes were investigated by various studies, no structured concept has been presented for a combined study of these main aspects and their interaction. The objective of this paper is to introduce the potential problem sources, propose a concept and present a workflow to understand and prevent problems related to geothermal reinjection in porous reservoirs. The workflow covers different scales and approaches, based on the problem sources. It is first tested at one example site (Mezőberény in SE Hungary) in order to demonstrate its ability, and to reveal the site-specific problems.

2. The workflow and the potential problem sources and approaches

2.1. *Workflow*

For a complete understanding of injection problems, the proposed workflow shows potential problem sources and approaches to analyse them on three different scales: the regional scale with the hydraulic state (overpressure and upward flow), the reservoir scale with reservoir properties (possible low extension, low permeability and performance), and the local scale with potential physical, chemical and biological clogging processes (particle migration, mineral precipitation and corrosion, biofilm formation) (Fig. 1). Example methods are given to show how to potentially address the problem. Site specific methods can be applied step by step having a regional then an intermediate and then a local scope. Interpretation of the results are proposed to be made for the different scales separately as well to integrate them.

2.2. *Potential problem sources and approaches*

Here the potential problem sources during geothermal reinjection are presented. At the same time we discuss the approaches and methods for analysing them to display the complexity of the proposed workflow.

2.2.1. *Regional hydraulics*

The involvement of preliminary regional hydraulic analysis complements the local and reservoir scale analyses. Hydraulic conditions will strongly influence the ease with which water can be injected, and they can also hinder low-pressure reinjection in case of abnormally high pressure in the aquifer (Mádl-Szőnyi and Simon, 2016; Mádlné Szőnyi, 2019). This effect was revealed e.g. at the geothermal sites of Kizildere and Salavatli (Turkey) located in overpressured reservoirs (Serpen and Aksoy, 2005).

Overpressure of the reservoirs at a certain depth is the significant difference between the pore pressure and the hydrostatic pressure at that depth (Verweij et al., 2012). Hydrodynamically overpressurized regimes are formed for instance due to tectonic compression or sedimentation and are preserved if sealed by a low conductive aquitard (Almási, 2003; Czauner and Mádl-Szőnyi, 2013).

The key point of the approach is the delineation of the boundary of overpressured and hydrostatic flow domains because they influence the reinjection potential (Mádl-Szőnyi and Simon, 2016). This is done by characterizing the pressure regime and specifying the direction of the vertical driving forces: overpressure and ascending driving force indicate the overpressured flow domain.

2.2.1.1. Overpressure – characterizing the pressure regime. To evaluate the pressure regime, we have to know the base effect of the topography on the water table which determines the hydrostatic conditions. The hydraulic gradient is the consequence of this effect, i.e., the differences of the elevation of the water table. This can cause so-called normal or hydrostatic pressure conditions under the water table in the saturated zone. Because the elevation of the water table is not known in most cases the average elevation (in m asl) of the ground surface area is used as a reference for calculating the hydrostatic pressure characteristic for the area of interest. If the pressure value of a reference point of a well deviates from the calculated hydrostatic values for that depth it is supposedly caused by geological reasons (Deming, 2002; Ingebritsen et al., 2006). If the real (measured) pressure values are significantly less or higher than the predicted hydrostatic values, it indicates either underpressured or overpressured regimes (Mádl-Szőnyi and Simon, 2016; Mádlné Szőnyi, 2020). This (positive or negative) deviation can be expressed by the term of the dynamic pressure increment (Δp), as the difference between the real or dynamic (p_{real}) and the hydrostatic or nominal pressure (p_{nom}) at the certain depth (Tóth, 2009):

$$\Delta p = p_{dyn} - p_{st} = p_{real} - p_{nom}$$

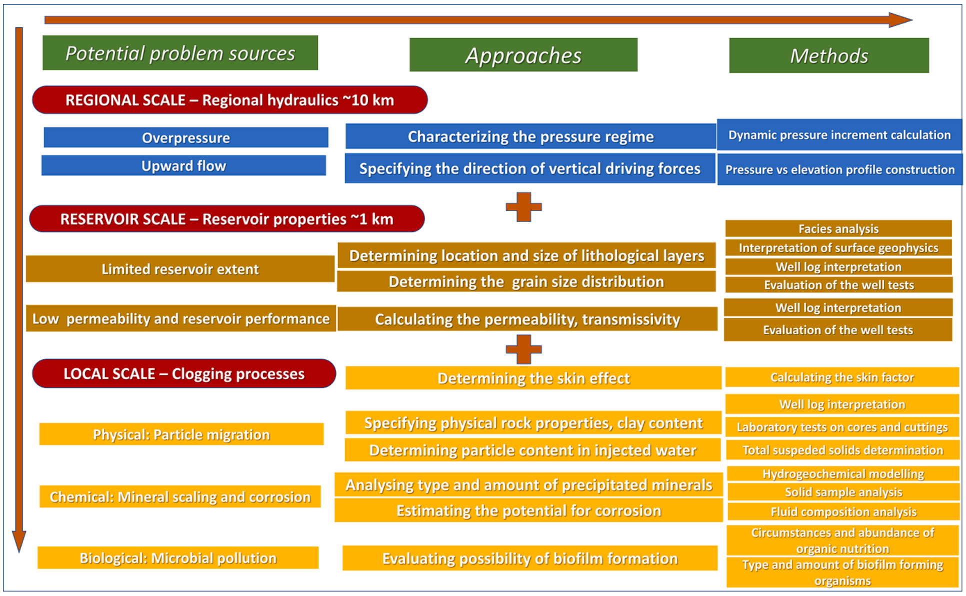

Fig. 1. Proposed workflow and approaches with example methods.

2.2.1.2. Upward flow – specifying the direction of the vertical driving forces. The magnitude of dynamic pressure increment (Δp) along a vertical length (Δl) is proportional to the strength of the vertical flow components. To determine the vertical component of the driving force of fluid flow, pressure-elevation [p(z)] profiles are constructed. On these profiles the pressure values from the close surrounding of the investigated system are displayed in the function of the elevation and compared to the ideal hydrostatic gradient. The latter should be determined using the average groundwater density for the investigated region (for instance, in case of freshwater density of 1000 kg*m^{-3}, y=9.81MPa*km^{-1}). The deviation of the vertical pressure gradient from the hydrostatic gradient indicates the hydrodynamic state, either into positive or negative direction (upward- downward flow) (Tóth, 2009). If $p_{dyn} < p_{st}$ the flow is downward and if $p_{dyn} > p_{st}$ the flow is upward with respect to water table.

2.2.2. Reservoir properties

For a successful injection into siliciclastic reservoirs, thick, highly porous, low-matrix (i.e., well sorted) sandstones are favorable, with little diagenetic change in their primary pore space and grain structures (Rockel et al., 1997). Their required petrophysical properties depend on the site-specific conditions; but the indicative parameters are effective porosity, permeability and reservoir thickness (Seibt and Kellner, 2003). In addition, reservoir architecture and facies heterogeneity (e.g., in fluvial reservoir systems) influence the doublet and thus the injection performance (Crooijmans et al., 2016). They control the reservoir connectivity which is linked to the net-to-gross ratio (N/G = net reservoir volume versus total volume) (Hovadik and Larue, 2007). The low connectivity of sandstone bodies can result in limited reservoir volume that can lower the injection capacity (Willems et al., 2017). At the reservoir scale (~1 km), a potential low reservoir extension, and a low permeability and reservoir performance are considered.

2.2.2.1. Limited reservoir extent. A low vertical extent (i.e., thickness) of a reservoir will ultimately result in a low transmissivity and thus injectivity. A limited horizontal reservoir extent will result in excess injection pressures when the pressure signal from the injection well encounters a lateral reservoir boundary (Renard et al., 2009).

To evaluate the vertical and horizontal extension of the reservoir, facies analysis and interpretation of depositional environment can be the first steps. Interpretation of surface geophysics (e.g., seismic data) helps in delineating the reservoir formations as well as identification of possible fault boundaries that may lead to aquifer compartmentalisation. Analysing the grain size distribution within samples or cuttings from the array of drilled production, injection and exploration boreholes and interpretation of well-logs recorded in the latter wells helps to determine the location, size and geometry of lithological layers. The sandstone content of the aquifer (net-to-gross (N/G)) is derived from the interpretation of well-logs. The length of the screened or filtered sections relative to the productive horizons should be considered. Additionally, identification of positive or negative boundary effects in well test hydraulic responses contributes to delineating the reservoir (Vandenberg, 1977).

2.2.2.2. Low reservoir permeability and performance. Permeability (k [m^2]) and transmissivity (T [m^2/s]) of the reservoir and the activity of the open sections are considered during the evaluation of the reservoir quality. The productivity and the injectivity index are more direct indicators of the reservoir performance. Productivity is the ratio of the total discharge (Q [m^3/d]) to the corresponding drawdown in head [m] or decrease in pressure increase caused by the production, while injectivity is defined as the reinjected flow rate (Q [m^3/d]) divided by the corresponding increase (i.e., upconing) in head [m] or pressure [Pa] measured in the injection well. According to Misstear (2001), the short-medium term injectivity or productivity of an efficient well should be around 1.22 to 2 times the transmissivity of the reservoir. These parameters can be evaluated using well tests e.g., pressure build up test, step-drawdown production test and injection tests.

2.2.3. Local clogging processes

Injectivity decline is often also related to clogging processes. This term covers the diverse mechanisms that result in the occlusion of flow pathways. These mechanisms have an effect both at the surface and downhole. The fundamental reason for the diverse mechanisms is that during the production and the reinjection the hydrodynamic and hydrochemical equilibrium of the fluids – which had been present before the well completion and operation – become disturbed (Szanyi et al., 2014). Controlling parameters that change during reinjection are temperature, pressure, flow velocity, salinity, redox potential and pH, which can lead to mobilisation of particles, microbial multiplication or to mineral precipitation or floc formation. As a consequence, the well bore, the sand face and the well can be plugged. This can lead to a positive skin effect i.e., extra flow resistance near the wellbore. It can be quantified by calculating the skin factor of the well to determine the scale of the problem (Agarwal et al., 1970). In case of fine-grained, clastic deposits (like sand, sandstone and clayey interbedded sequences), formation damage can occur by plugging of the pore throat, resulting in permeability reduction (Seibt and Kellner, 2003; Ungemach, 2003). Similarly, pore spaces and throats can be clogged by trapped gas bubbles (Boisdet et al., 1989). The consequence of these processes is injectivity decline. Chemical, biological, as well as physical processes should be considered in the framework of clogging (Brehme et al., 2018).

2.2.3.1. Physical processes (Particle migration) – specifying physical rock properties, determining the particle content of the injected water. Among the source of migrating particles, reservoir formation (i.e., formation fines, either mobilized from the reservoir and transported to the surface, or mobilised and redistributed in the reservoir around the injection well) and the pipeline and surface facilities should be distinguished.

The term formation fines involve small grains (fine sands, silts and clays) present in porous media. The migration of fines includes the whole array of release of fine particles, their motion with the flow and their trapping in pores or leaving the porous media (Khilar and Fogler, 1988). Considering the capture mechanisms, filtering is the most probable way for the redeposition of particles. Consequently, flow paths of the porous medium become blocked resulting in injectivity decline (Sharma and Yortsos, 1987; Ochi and Vernoux, 1998).

The source of formation fines is depending on the reservoir formation, its physical properties, mineral composition, clay content and grain size (Sharma et al., 1985). The properties can be understood from core samples or well logs that indicate grain size. In an intact system, minerals and fine particles are in equilibrium with the pore fluid. When this equilibrium is disturbed by the diverse processes triggered by the production and the injection, minerals may be dissolved and fines may be displaced (Civan, 2007). Above the critical flow velocity (CFV) fines migration occurs and often leads to zones of permeability decline, while below the CFV permeability decreases were not detected (Gruesbeck and Collins, 1982). Also, the critical salt concentration (CSC) controls fines migration. Core flood experiments showed: if the salinity drops below the CSC, clay particles are released and transported by fluids (Khilar and Fogler, 1984).

The main origin of solid fine particles mobilised from the pipeline at the surface are mineral scales, corrosion- and biological products. The (chemical and biological) processes behind their original formation are detailed in the following two subchapters.

Measuring the suspended solids in water samples quantifies their amount and size. Particulate (suspended solids) content and turbidity of injected and produced waters should be routinely monitored. The technical details of the installed filter system in the wells and at surface are important, because they prevent the inflow and the migration of the fine particles into the well and the reservoir; thus they have to appropriately fit to the expected site-specific suspended solids. Different types of filters can be used to reduce the risk: well screen / gravel pack in production well; in line filters, sediment traps or cyclones in the pipeline; screen in injection well.

2.2.3.2. Chemical processes (mineral precipitation and corrosion) – estimating the type and amount of precipitation and the potential for corrosion. Mineral precipitation, also known as scaling, has been observed during exploitation of geothermal resources and cause major drawbacks (Corsi, 1986). The forming of scales is mainly induced by thermodynamic changes: cooling of the fluid, pressure change, degassing, pH changes redox changes and exposure to oxygen, chemical reactions due to mixtures of waters of differing chemical types. Scaling types can be differentiated based on their place of occurrence: in-hole scaling (in the well), formation plugging (precipitates in the formation) and surface scaling (in surface facilities such as heat exchanger and pipelines) (Corsi, 1986). Moreover, precipitated solid particles can be suspended in the geothermal fluid, and migrate through the geothermal loop, resulting in plugging mechanisms around the reinjection well detailed above (Ungemach, 2003).

Predicting and quantifying chemical processes during operation is done using hydrogeochemical modelling with e.g., PHREEQC software (Rockel et al., 1997). Simulating the production and reinjection process gives the saturation state of different minerals: a supersaturation indicates precipitation of that mineral. The use of such models, however, is dependent on reliable high-quality analyses of the water. It can be very difficult to obtain consistently good determinations of some parameters, that strongly affect the risk of scaling, such as redox potential and dissolved gas concentrations. Solid phase analysis (e.g., X-ray Diffraction, X-ray Fluorescence) on material sampled from filters (i.e., filter residuals) and well bottom validates the model outcomes.

Fluids of geothermal systems also transport to the surface several chemical species that can cause corrosion on metallic construction materials: oxygen, hydrogen ion (i.e., pH), chloride ion, hydrogen sulphide, carbon dioxide species, ammonia species, sulphate ion (Corsi, 1986; Ellis and Conover, 1981). In addition to these impurities, corrosion and its quantity is influenced by the type of materials, by the interaction of one or more chemical species and by the form of the attack: uniform corrosion, pitting, crevice corrosion, stress corrosion, cracking and corrosion fatigue (Corsi, 1986; Ellis and Conover, 1981). On top of the destructive effect of corrosion, transported corrosion products contribute to clogging (Brehme et al., 2018; Boch et al., 2017). To estimate the potential for corrosion, analysing the fluid composition in respect to the above listed parameters can be helpful.

2.2.3.3. Biological processes (microbial activity) – evaluating the possibility of biofilm formation. Microbial components in thermal waters are most commonly from groups of thermophilic bacteria (range of most intensive metabolism: 50-60 °C) and mesophilic bacteria (optimum temperature: 20-40 °C) (Taylor and Vaisman, 2010; Szanyi et al., 2015). In more extreme conditions, bacteria use resistant spores to stay alive in unfavourable circumstances (high temperature, high salt concentration), so that they continue the metabolism and reproduction in favourable conditions. During geothermal production, mesophilic bacteria are present by these spores without an operational-problem raising metabolism (Szanyi et al., 2015). Though, the conditions of heat-depleted (cooled) water to be reinjected are ideal to the mesophilic microorganisms. Therefore, they start to proliferate and their vast majority form biofilms. Biofilms are formed by well-organized communities of microorganisms attached to a surface in wet environments, assembling both living and dead cells and additional organic and inorganic particles (Sand, 2003; Czinkota et al., 2015; Szanyi et al., 2015). They act as fluid flow barriers and thus they are mainly responsible for operational and reinjection problems related to microbes: e.g., need of frequent change of filters and higher injection pressure (Osvald et al., 2017).

Microbial growth is strongly dependent on external circumstances i.e., temperature and pH, while the organic content and nutrition sources (e.g. nitrogen or phosphorous compounds) determine the microbial flora (Sand, 2003; Osvald et al., 2017). Microbial composition tests of water samples and filter residuals provide information about quality and quantity of microbial activity and its probability to form biofilm.

3. Example study area

The Mezőberény study site is located in the South-Eastern Great Plain of Hungary (Fig. 2), in the Békés Subbasin of the Pannonian Basin.

3.1. Geothermal background of Békés Basin in the Pannonian Basin

The Pannonian (back-arc) Basin started to form in the Early Miocene (Horváth et al., 2015). The basin was later filled with the so-called Pannonian sediment sequence: less permeable deep-water Pannonian sediments (Endrőd, Szolnok, Algyő Formations) – proven as hydrocarbon reservoir as well –, followed by the shallow-water Pannonian deposits (Újfalu, Zagyva) – hydrocarbon reservoir with mostly immature organic matter. Their current thickness can reach 6000 m in the Békés Basin – a deep subbasin located in the SE part (Grow et al., 1994). Medium to fine-grained sandstone and siltstone lithofacies sedimented in shallow-water delta and shoreline environments (Újfalu Formation), overlain by a thin-bedded alternating siltstone-sandstone-claystone succession, formed in an alluvial plain with meandering streams (Zagyva Formation) (Juhász, 1992; Sztanó et al., 2013). Újfalu and Zagyva formations contain porous, permeable sandstone beds with thicknesses between 1 and 30 m (Bobok et al., 1984). These aquifer bodies have a bulk porosity of 20-30 % and a permeability of 500-1500 mD (Bobok and Tóth, 2003; Tóth and Almási, 2001). These shallow-water Pannonian siliciclastic rocks are one main geothermal reservoir in the Pannonian Basin (Tóth A., 2015). From a hydrostratigraphic point of view shallow-water Pannonian (Zagyva and Újfalu) Formations and the Quaternary sediments form the Great Plain Aquifer (GPAF) with an average hydraulic conductivity (K) of 10^{-5} m/s (Tóth and Almási, 2001). Hydrogeologically, the Pannonian Basin can be divided into two regimes: an upper, regionally unconfined, topography driven system, and an underlying overpressured regime, with lateral tectonic compression and burial compaction causing overpressure (Almási, 2003; Tóth and Almási, 2001). A transition zone is formed between the two regimes (Czauner and Mádl-Szőnyi, 2011; Tóth and Almási, 2001). Due to the thinned lithosphere a positive heat anomaly is present with an average geothermal gradient of 45°C/km (Dövényi and Horváth, 1988).

3.3.1. Mezőberény study site

The geothermal system of the town was constructed in 2011-2012, with the aim to utilize the geothermal potential in the Békés Basin for a district heating system. The system consists of one production well (B-115) with a depth of 2003 m and one reinjection well (K-116) with a depth of 2001 m, located on a NW-SE striking profile at 1.2 km distance (Fig. 3). They are cased, completed with liners until 1.6 km and screened with 0.5 mm mesh size Johnson Filters, including an 1-2 mm grain-size gravel pack at the depth of the siliciclastic reservoir layers of the Zagyva and Újfalu formations (Table 1).

On the production side, a submersible pump is producing thermal fluid to the surface, where it flows to a buffer tank. The buffer tanks can absorb large fluid volumes at the start of production and also serves as a degassing tank. After degassing, booster pumps forward the water through quartz-sand filters with a mesh size of 100 μm and the heat of the water is transferred by separate (1. heating circle) and central (2. heating circle) heat exchangers to the heat consumers. The heat-depleted water flows into a buffer tank and is reinjected by injection

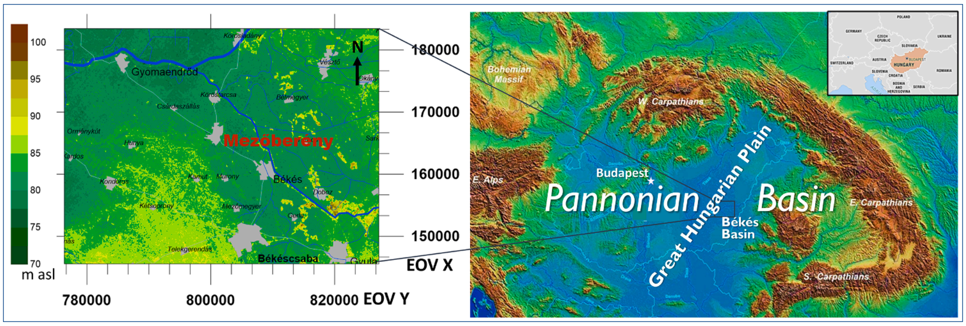

Fig. 2. Location of the study site.

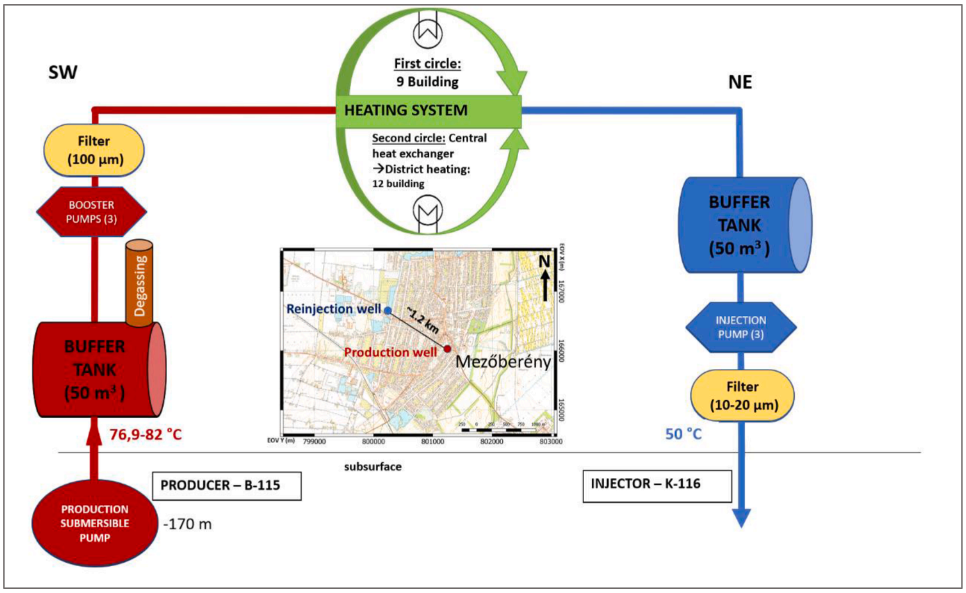

Fig. 3. Schematic figure of Mezőberény geothermal site.

Table 1
Basic data of Mezőberény geothermal doublet

	Mezőberény Producer	Injector
Number	B-115	K-116
Year of drilling	2011	2012
Elevation asl (m)	85.44	85.32
Bottom depth (m)	2003	2001
Reservoir rock	Shallow-water Pannonian Sandstone	
Reservoir interval containing screened sections (m)	1826-1947	1643-1931
Cumulative length of well screen (m)	27.5	75.5
Static water level	-9.53 m 75.91 m (asl)	-7.56 m 77.76 m (asl)
Bottom hole temperature (°C)	109.7 (at 1995,5 m)	111.3 (at 1989 m)
Outflow temperature (°C)	76.9	83.2
Operational flow rate (l/min)	350 (producable)	250 (injectable with 1.5-2 bar)

pumps first passing through filters (10-20 μm, polypropylene filter bags) into the injection well (Fig. 3) (VITUKI., 2011; VITUKI., 2012; TT KTFV, 2012).

Water and gas were sampled after well completion from the production and injection wells (Table 2, Table 3). The fluid (in both wells) had a substantial gas content (specific total gas content: production well: 1723 L/m^3; injection well: 1670 L/m^3) which consists of predominantly methane (specific total methane content: production well: 962 L/m^3 injection well: 1272 L/m^3). Its utilisation and disposal have not yet been solved, as the planned degassing method was not permitted by the authorities due to its high amount. During the short operational period, the degassing method was applied (Siklósi, 2017).

After a 3-week operational period at the end of 2012, injectivity has radically dropped, so that the operation had to be stopped. After long discussion on the potential reasons for unsuccessful operation, in 2016-2017 mechanical and chemical (with 0.5 % HCl solution) cleaning was carried out to remove clogging material from the wells downhole. The system was tested with tap water; however, it did not go into operation again due to lack of understanding of the injection problems using the produced brine. A long-term solution for increasing and stabilizing the injectivity has not been found yet (Siklósi, 2017; Brehme et al., 2019; Brehme et al., 2021; Willems et al., 2021).

3.4. Reference reinjection sites

There are several analogue sites in Hungary with similar geological and hydrogeological settings and ongoing reinjection. In this study, some of their parameters will be cited and compared to our study site (based on Markó (2020)). The four analogue systems, with 1 or 2 injection wells each, are Hódmezővásárhely, Szeged, Orosháza and Kistelek – situated within 40-70 km distance from Mezőberény, all in the South-East part of the Great Hungarian Plain. All five systems presented have similar lithostratigraphic settings, they are settled in

Table 2

Water composition of the wells (Production = produced from the production well; Injection = water produced from the injection well)

Sample	Unit	MEZŐBERÉNY B-115	K-116
Well type		Production	Injection
Location of sampling		surface	surface
Flow rate during sampling	L/min	*310*	*285*
Sample date		*2011 September*	*2012 June*
pH	-	7.5	7.6
Electrical Conductivity (20°C)	[µS/cm]	5600	5360
Total Dissolved Solids - TDS	[mg/L]	6705	4743.86
T	[°C]	76.9	75
HCO_3^-	mg/L	4470	4570
F^-		1.7	1.56
Cl^-		268	148
Br^-		2.2	2.6
I^-		2.9	2.6
NO_3^-		<1	<0.02
SO_4^{2-}		20	19
Na^+		1860	1770
K^+		30	28
Ca^{2+}		13.7	17.2
Mg^{2+}		3.7	5.9
Fe		7.5	4.8
Mn		0.1	0.09
Li^+		0.55	0.49
Ba^{2+}		1.99	1.99
SiO_2		79	79
NH_4^+		24.4	28
PO_4^{3-}		0.24	0.1

Table 3

Separated gas composition of the fluid sample (Production = pumped from the production well; Injection = water produced from the injection well)

	Mezőberény (%) Production	Injection
	B-115	K-116
O_2	0.73	0.72
CO_2	37.71	14.29
N_2	2.63	3.3
CH_4	58.93	81.66

Pannonian sandstones, Zagyva and Újfalu Formation. The wells (5 production and 10 injection wells) are screened in the sandstone layers of the alternating sandstone-siltstone-clay-marl layers of the formation (Table 4.

4. Application of the workflow with site specific methods and data

4.1. Regional hydraulics

4.1.1. Potential overpressure – characterizing the pressure regime

To characterize the pressure regime, we calculated the dynamic pressure increment for the two wells of the Mezőberény doublet system and for four other groundwater wells in Mezőberény.

First, we determined the ideal hydrostatic pressure at the elevation of the reference point using an average water table elevation of $z_{Wt(average)}$=90 m:

$$p_{hydrostatic} = \left[z_{Watertable(average)} - z\right] \times \rho \times g \times 10^{-6}[\mathrm{MPa}]$$

We used a density of 1000 kg*m^{-3} following the density correction calculation of Czauner (2012) for the region of Békés-basin.

After that we defined a quasi-hydrostatic pressure range for the study area (based on Mádlné Szőnyi, 2020) using the minimum ($z_{Wt(min)}$ = 80 m) and the maximum ($z_{Wt(max)}$=100 m) elevation of the ground surface: phydrostatic + [ρ × g × ($z_{Wt(max)}$ − $z_{Wt(min)}$)/2 × 10^{-6}] ≤ pdynamic [MPa] phydrostatic − [ρ × g × ($z_{Wt(max)}$− $z_{Wt(min)}$)/2 × 10^{-6}] ≥ pdynamic [MPa]

$$p_{hydrostatic} + \left[\rho \times g \times \left(z_{Wt(max)} - z_{Wt(min)}\right) / 2 \times 10^{-6}\right] \leq p_{dynamic}[\mathrm{MPa}]$$

If the pressure of the reference point exceeds these limits, it is abnormal, either underpressured or overpressured. The deviation of the real pressure from the ideal hydrostatic at the reference point can be expressed by the pressure increment (Δp_{dyn}):

$$\Delta p_{dyn} = p_{real} - p_{hydrostatic}$$

4.1.2. Potential upward flow – specifying the direction of the vertical driving forces

To determine the direction of vertical flow driving forces, a pressure-elevation profile was constructed for the (5 × 5 km) study area of Mezőberény, using the available data from 6 wells (including the

Table 4

Geological and structural data of the study and reference wells

	Well type	Number of the well	Year of drilling	Well end depth (m)	Reservoir rock	Screened reservoir depth (m)	Cumulative length of opened sections (m)	Reservoir temperature (bottom hole temperature) (°C)	Outflow temperature (°C)
Mezőberény	Production	B-115	2011	2003	Shallow-water Pannonian Sandstone (Zagyva and Újfalu Formation)	1826-1947	27.5	109.7	76.9
	Injection	K-116	2012	2001		1643-1931	75.5	111.3	83.2
Hódmezővásárhely	Production	B-1092	1996	2013		1832-1997	58.38	84.2	73.5
	Injection	B-1094	1997	1685.5		1473-1669	79.12	72	61
	Injection	B-1077	1984	2295		1368-1601	81.5	135	86
	Injection	B-1103	2007	1702		1482-1677.8	89.75	71.9	65.7
Orosháza	Production	B-770	2004	1560		1415-1553	66	101.2	88.2
	Injection	K-775	2011	1558-1565		1475-1533	43	104.5	84.5
	Injection	B-776	2011	1565		1417-1555	54	100.5	88
Kistelek	Production	B-46	2003	2095		1972.15-2072.5	49.94	90.6	82
	Injection	K-49	2006	1702		1468.5-1671.7	61.4	71.5	58.3
Szeged	Production	B-748	2014	2018		1704.2-1875.7	88.1	101.4	76.9
	Injection	B-744	2013	1389		1112-1381	127	56.5	55.7
	Injection	B-745	2013	1760.5		1631-1736	64	82.7	75.6
	Injection	B-746	2014	1745		1480-1704	59	92.3	64.6

doublet of the study system) screened to the Great Plain Aquifer. Hydrostatic gradient with 9.81 MPa*km^{-1} was used and pressure was calculated from static hydraulic head measurements by assuming a density of 1000 kg*m^{-3} based on the regional (Békés-basin) density correction calculations of Czauner (2012).

4.2. Reservoir properties

4.2.1. Low reservoir extension

We present the natural gamma ray log (carried out after well completion) of the Mezőberény injector to review the position of the screened layers. Based on the gamma log, we estimated the grain-size conditions of the reservoir, describing the quality of the reservoir layers. Additionally, we gathered the length of the sections of the formation open to the well via filter screen and calculated the total, the maximum and the average thickness of the screened sections.

4.2.2. Low reservoir permeability and performance

The distribution of productivity over the screened sections and their operating (active) length has been measured during well testing. The permeability of the layers was determined through a pressure build-up test, that had been carried out after the well completion. Adding the thickness of the screened sections, we calculated the transmissivity of the aquifer.

Another indicative parameter is the productivity index of the well, which is defined as the flow rate per unit pressure drop and was determined by the step-drawdown production test. The production parameters had been measured with two stable flow rates, during which water level and pressure have been measured. Based on that, the change of the hydraulic head and pressure (compared to the static state) were calculated.

4.3. Local clogging processes

4.3.1. Physical processes (particle migration) – specifying physical rock properties, clay content

Rock physical properties and mineral composition including content of clay minerals of the rocks is based on literature (Juhász, 1992; Kovács et al., 2015; Szanyi et al., 2015; Thamóné Bozsó et al., 2006; GeoCom, 2013; Willems et al., 2021) due to lack of in situ core samples. The gamma ray log indicates grain size distribution in the screened reservoir sections. Additionally, we examined the properties of the underground filters and the filter system at surface in respect to the mesh size, i.e., which solids they are able to filter.

4.3.2. Chemical processes (mineral precipitation) – type and amount of precipitation

We used hydrogeochemical modelling with PHREEQC Version 3 software (Parkhurst and Appelo, 2013) to simulate the chemical processes. To perform the modelling, a conceptual model was set up in Markó et al. (2021a) to cover the processes of the geothermal utilization Model step 1.: The fluid composition and its physicochemical properties at the production well. Model step 2.: Contact of the production fluid with air by adding a gas phase with a composition of 78% nitrogen, 21.6% oxygen, 0.4 % carbon-dioxide. Model step 3.: Fluid composition and its physicochemical properties at the injection well and the minerals in equilibrium with that fluid at depth. Model step 4.: Mixing of the two fluids from production site and injection site. Mixing state is considered with approximately 85% production fluid (i.e., to be reinjected) and 15% injection well solution (i.e.: sampled from the injection well before injection). This mixture aims to represent a dominance of the injected fluid in the reservoir.

Saturation indices of minerals are calculated by solving the equation for each mineral: $SI=\log10(IAP/K_{mineral})$ where SI = Saturation Index, IAP = Ion Activity Product and K = solubility constant for the mineral (Parkhurst et al., 1980). SI = 0 indicates that the mineral is in equilibrium with the solution. If SI is < 0 the solution can dissolve additional minerals. If SI is > 0, the mineral is supersaturated and will possibly precipitate with time. To estimate the amount of the possibly precipitating mineral, the PRECIPITATE_ONLY command is used to get the amount of precipitation in mol/L.

For model calibration purposes we use solid material that was sampled from the surface installations in August 2017. Samples are from the injection well, injection well pipeline, injection well outlet pipe and two samples flushed into the filters from the reservoir during cleaning of the injection well in 2017. X-Ray powder Diffraction analysis was done with all solid samples in March 2018 to understand which minerals are precipitated during normal operation.

Further details on our investigation can be found in Markó et al. (2021a).

4.3.3. Biological processes (microbial activity) – evaluating the possibility of biofilm formation

Water and gas analysis were carried out after the well completion (2011: production well, 2012: injection well) on the chemical composition, pH, temperature, total organic carbon, and – in case of the production well – organic components as well. Additional water samples were taken at three different locations (pure thermal water and two from the filter system), for microbial analysis (i.e., DNA sequencing) (Xenova, 2017). We reviewed the type of the detected species on their abundance and biofilm forming ability. We considered temperature, pH state, planned operational parameters of the system and the possible nutrition sources to analyse whether the reservoir and plant conditions are favourable for microbial growth.

5. Results for the study area

5.1. Regional scale hydraulics

We analysed the hydraulic conditions of the aquifer on a regional (~10 km) scale through characterizing the pressure regime. A more extensive study in this framework was done by Markó et al. (2021b).

5.1.1. Potential presence of overpressure

The potential presence of overpressure can be detected through the calculation of the pressure increment from the hydrostatic pressure at the reference point of the investigated well(s). Based on the elevation differences of the ground surface we defined the range of the quasi-hydrostatic pressure increment to then be able to detect the abnormal pressure exceeding these limits. Based on the elevation range of the topography of the study area (maximum elevation: 100 m asl, minimum elevation: 80 m asl), the quasi-hydrostatic range is: +/- 0.1 MPa.

Pressure increments at the Mezőberény study system show slightly subhydrostatic conditions with Δp= -0.12 MPa (injector) and Δp=-0.14 MPa (producer). Other values from the shallower (groundwater and thermal) Mezőberény wells fit into a quasi-hydrostatic zone with a range of Δp= -0.02 to Δp=0.07 MPa.

5.1.2. Potential presence of upward flow

To define the direction of the vertical component of fluid flow driving forces and detect potential upward flow, we compiled a pressure-elevation profile for the Mezőberény area (5 × 5 km). Pressure data points (orange triangles) calculated from static water level in nine groundwater wells screened to the Great Plain Aquifer (GPAF) are shown together with the gradient-line of the ideal hydrostatic gradient (Fig. 4). Based on that, vertical pressure gradient at the latter Aquifer is y_{GPAF}=9.75 MPa/km, which is lower than the ideal hydrostatic value (y=9.81 MPa/km).

5.2. Reservoir properties

We analysed the reservoir extension, permeability and performance

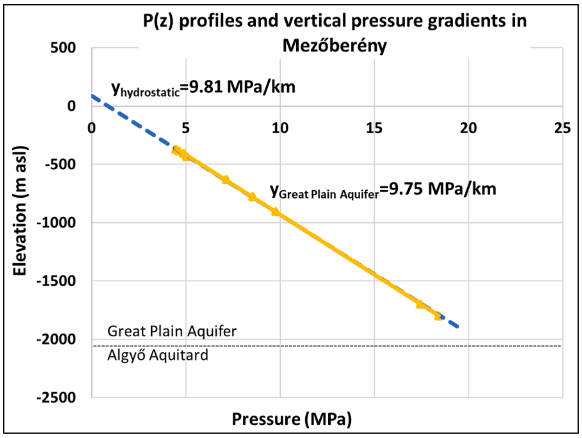

Fig. 4. Pressure elevation [p(z)] profile and vertical pressure gradient in Mezőberény (orange) with the ideal hydrostatic gradient line (dotted blue).

as indicators of potential unfavourable reservoir properties.

5.2.1. Low reservoir extension

A natural gamma ray log has been measured in the injector of Mezőberény after well completion in 2012. Fig. 5 shows the well interval between 1520 and 2000 m depth covering the length of the reservoir. We used the outcomes to determine the grain size distribution in the reservoir interval and the screened sections. The natural gamma log shows alternating low and high grain size segments of the siliciclastic unit, where the gamma lows (sandstone grain size) have a thickness between 1-10 m (e.g. at 1745-1755 m depth, Fig. 5).

The injection well is screened with Johnson filters, shown by checked rectangles (I-XII.) in Fig. 5. Screens are generally positioned in low-gamma ray (large grain size) zones. However, some of the sections are positioned in units with relatively high values of around 10 μR/h. Hence, screen II., V., VII. and VIII. cover rocks with possibly lower grain size.

The twelve screened sections of the injector have a net thickness (total length) of 75.55 m. Meanwhile, the average thickness of the sections is 6.29 m, and the longest section is 11.64 m long. We consider the length of the screened sections as an indicator of the utilizable reservoir length.

5.2.2. Low permeability and low reservoir performance

Well productivity tests have been performed in the injection well after completion in 2012. Evaluating the well tests allows us to conclude on the general reservoir performance.

The flow rate from the screened sections was measured during a well-test to be 7.67 L/s in total: Based on the flow meter log, out of the total 75.55 m screened section, 43 m were active, namely producing water. The productivity of the individual screened sections differs strongly and 70 % of the flow rate comes from three sections: IV: 1745-1755 m (1.83 L/s); X: 1891-1893.7 (1.16 L/s); XII: 1920-1927.6 (2.33 L/s).

A pressure build-up test was conducted by producing from the well with a 7.67 L/s flow rate for 420 minutes and a stabilized head of +48.44 m (above ground level), followed by a shut-in with pressure increase recording. At the end of the 120-minute shut-in period, the experiment was stopped without reaching steady state with constant pressure. The average permeability of the reservoir for the total screened length (75.55 m) was determined to be: $k = 5.04*10^{-14}\ m^2 = 50.4$ mD. The average permeability of the operating length (where the inflow technically occurs=43.3 m) is $k' = 8.79*10^{-14}\ m^2 = 88$ mD. Using this permeability value and the screened length, we calculated a reservoir transmissivity of: $T = 1.26*10^{-4}\ m^2/s$.

Additionally, a step-drawdown production test was carried out at two stable flow rates of 4.75 L/s and 8.4 L/s. Flow rate and pressure (at

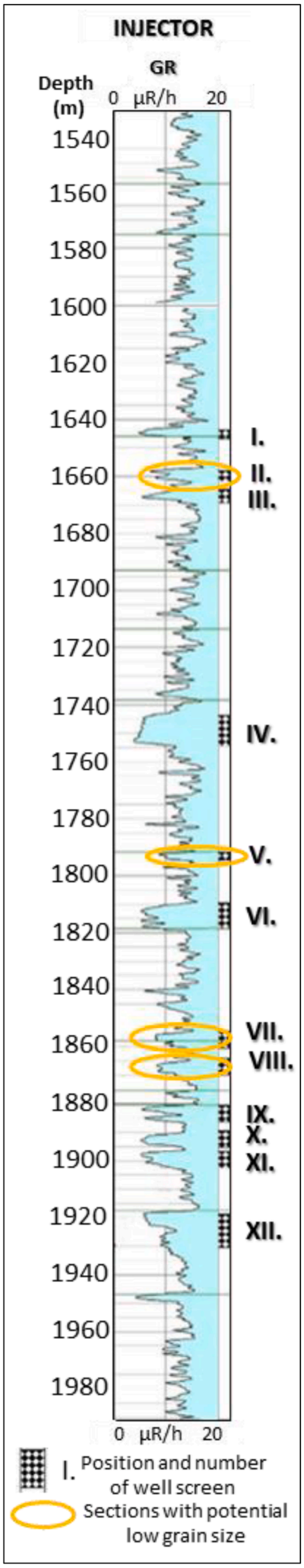

Fig. 5. Natural gamma log of the injection well.

1600 m) were measured for 135 minutes. The change of pressure (compared to static state) was calculated by dividing the maximal flow rate of 8.5 L/s by the pressure change (0.4303 MPa): The productivity index is 19.75 L/s/MPa = 1707 m^3 /day/MPa.

5.3. *Clogging processes*

Local clogging processes were analysed using data from field tests. Various material types and different grain sizes were found during cleaning of the injector well e.g., precipitated minerals and biofilm were recovered from the screens downhole. Clay particles were also detected causing a yellow-coloured production water. We examined these aspects systematically on physical, chemical and biological processes.

5.3.1. *Physical processes – particle migration*

As physical process, we investigated the release of formation fines which can lead to clogging. To asses the risk of fines release we considered the rock properties of the formation in respect to the grain size distribution and rock physical properties:

The reservoir (Újfalu and Zagyva) sandstone formations are interbedded by siltstone and claymarl sections (Juhász, 1992). Both formations are loosly cemented and weakly consolidated (Kovács et al., 2015; Willems et al., 2021). Additionally, they are poorly sorted, with a relatively high clay content (Szanyi et al., 2015). Based on micro-minerological and XRD analysis from literature, Pannonian reservoir rocks contain clay minerals: chlorite and kaolinite (Thamóné Bozsó et al., 2006; GeoCom, 2013).

To be able to observe these characteristics at Mezőberény, natural gamma logs were again used to reveal the grain size distribution of the screened sandstone bodies. As mentioned in the reservoir properties subchapter, well screens of the injection well span also segments with a potential lower grainsize (II, V, VII, VIII and to a certain extent IX, XII as well). Contrary to that, production well screens cover rocks with generally higher grain size.

5.3.2. *Chemical processes – mineral scaling*

Chemical data from fluids and solids with physicochemical properties have been combined in a hydrogeochemical model to simulate the dissolution and precipitation processes in four steps: the fluid-air contact, the changing temperature, the mixing of the reinjected fluid with the reservoir fluid, and the interaction with the reservoir minerals (Parameters: Table 5).

The main outcomes of the PHREEQC model are the saturation indices (SI) showing the possibility of precipitation of each mineral. The following minerals were chosen to be relevant for the system: iron and manganese oxides and hydroxides, carbonates, barite, silica, and gypsum based on literature (Corsi, 1986; Regenspurg et al., 2010; Brehme et al., 2018). The supersaturated minerals in Mezőberény are carbonates (calcite: SI=0.54, aragonite: SI=0.42, dolomite: SI=1.07) and iron-(goethite: SI=8.78, hematite: SI=19.71) and manganese minerals (hausmannite: SI=3.43, pyrolusite: SI=4.84). Meanwhile, amorphous silica (SI=-0.43), gypsum (SI=-4.49), barite (-0.93) and manganite (SI=-0.79) are undersaturated.

To transfer the qualitative evaluation into a quantitative estimation we modelled the quantity of mineral scale potentially formed in mol/L. Based on the outcomes, calcite and goethite have the highest value with $1.2*10^{-4}$ mol/L, followed by dolomite ($8.9*10^{-5}$ mol/L), hematite ($5.7*10^{-5}$ mol/L) and pyrolusite ($1.6*10^{-5}$ mol/L). However, iron does not immediately form hematite after contact with oxygen but forms ferric oxyhydroxide flocs. As our model calculation is not able to predict the saturation of the latter, we use the amount of hematite instead.

In addition to the hydrogeochemical modelling, X-Ray Diffraction analysis was applied to two samples from filter residuals. The results serve as validation for the model outcomes. Results show the following minerals being present at the injection wellhead precipitated during the normal operation: calcite ($CaCO_3$), goethite (FeOOH), magnesioferrite ($Mg(Fe^{3+})_2O_4$) and magnetite (Fe_3O_4). Samples from the productivity test during the cleaning of the injector (i.e., technically from the injection well and the reservoir) consist basically of siderite ($FeCO_3$) and halite (NaCl).

5.3.3. *Biological processes – biofilm formation*

To understand the organic processes, we considered the physicochemical circumstances and potential nutrition sources for microbes: Temperature, pH, total organic carbon (TOC) and phenol index. These parameters were measured during the fluid analysis after well completion. The measured parameters are in similar ranges in the two wells (Table 6). In case of the production well, organic compounds were analysed in more detail (i.e., BTEX: benzene, toluene, ethylbenzene, xylene; PAH: Polycyclic Aromatic Hydrocarbons were measured – Table 6).

Additional factors influencing the microbial growth are oxygen and temperature in the system. As the Mezőberény geothermal system includes two open buffer tanks to temporarily store fluids (after production and before reinjection), the fluid can come into contact with air. The planned injection temperature in Mezőberény is 50 °C, which means a temperature decline of 30°C compared to the production temperature (TT KTFV, 2012).

A microbial test on samples from the filter system and the thermal water shows a number of microbes in samples from the filter tanks, while a sample from the thermal system (i.e., produced water from the production well) itself differs clearly from the filter samples with also less detected organisms in total (Xenova, 2017). Based on DNA sequencing the microbial composition generally indicates the presence of mostly anaerobic and mesophilic groups (Fig. 6).

Table 6
Parameters of fluids in the production and injection well (NM=not measured) (Production = pumped from the production well; Injection: water produced from the injection well)

Parameter	Units	Production well	Injection well
pH		7.5	7.6
Temperature (outflow)	°C	76.9	75
TOC	mg/L	1260	1360
Phenol index	μg/L	6000	5540
Benzene	μg/L	87	NM
Toluene	μg/L	120	NM
Ethylbenzene	μg/L	23	NM
m-and p-xylene	μg/L	22	NM
o-Xylene	μg/L	34	NM
All Polycyclic Aromatic Hydrocarbons (PAH)	μg/L	0.339	NM

Table 5
Parameters used in the hydrogeochemical model (fluid compositions: Table 2, Table 3)

Injected fluid composition	Reservoir fluid composition	Injection temperature	Reservoir fluid temperature	Air contact	Injection pressure	Mixing ratio	Reservoir mineral composition
Mezőberény producer (B-115)	Mezőberény injector (K-116)	50 °C*	111.7 ℃	yes	1 atm	~85% Injected fluid + 15% Reservoir fluid	quartz, K-mica, dolomite, albite, chlorite, calcite, goethite, illite

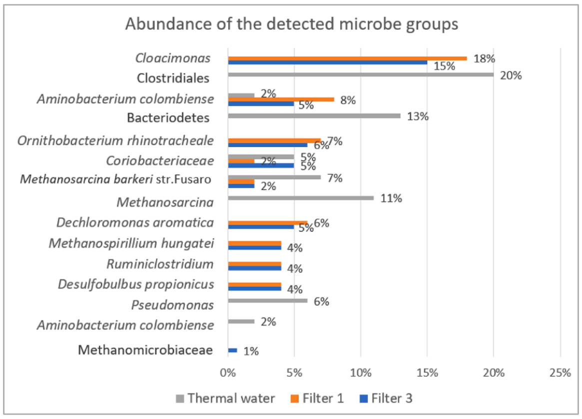

Fig. 6. Abundance of detected microbes in the samples of the filter system Mezőberény (most abundant microbes based on Xenova (2017)).

6. Discussion

6.1. Interpretation of the hydraulic conditions at a regional scale

Calculating the dynamic pressure increment and the vertical pressure gradient allowed to characterize the subsurface pore pressure regime that determines the injection capacity – as proposed by Mádl-Szőnyi and Simon (2016). The quasi-hydrostatic and subhydrostatic pressure increments in Mezőberény do not show presence of overpressure in the regional flow domain. As the vertical pressure gradient is slightly subhydrostatic, ascending vertical flow is not expected. Consequently, unlike several regions of the Pannonian Basin (investigated and presented by e.g., Tóth & Almási, (2001); Czauner & Mádl-Szőnyi (2013); Mádl-Szőnyi & Simon (2016)) unfavourable hydraulic conditions with elevated pressure or ascending flow could not be observed in our study area. The reason for that is most likely the thick and continuous underlying regional aquitard (Algyő Formation and Szolnok Formation to some extent) that blocks the local overpressure dissipation from beneath (Markó et al., 2021b). Therefore, a drawback in injection caused by hydraulics is not expected at the study site, the slightly subhydrostatic regime provides beneficial conditions for reinjection from a hydraulic perspective.

6.2. Interpretation of the reservoir properties at a reservoir scale

Reservoir properties analysed using the well-logs and completion data of the well show that the net reservoir thickness, 75.55 m highly exceeds the 'indicative minimum net thickness'. The latter is a defined value being >20 m for sedimentary aquifers, first mentioned by Rockel et al. (1997) and Seibt & Kellner (2003) based on the experience in the projects that had been carried out in the North German Basin. The value for Mezőberény is therefore higher than the optimal value, which indicates a sufficient total vertical extension. Considering the individual length of the separate screened sections of the well, they generally show a lower length compared to other injection wells in similar geological settings. The average length of separate screens at the nine 'reference' injectors has a range of 8.6 m to 25.4 m, while this value at Mezőberény injector is 6.29 m (Table 7) (Markó, 2020).

The small value originates from the low vertical thickness of the sandstone bodies, for which reason the screened sections had to be designed shorter in Mezőberény. The latter can also be inferred from the net-to-gross ratio of the reservoir (9 % - determined by Willems et al. (2019)) which indicates a low sandstone content in the reservoir formation. According to them, not only the vertical length of the sandstone bodies intersected by the wells is small, but their horizontal width as well – demonstrated through geological modelling; thus resulting in a in small net reservoir volume (Willems et al., 2019). A fundamental reason for these geologic characteristics can be the frequent changes in the deltaic and alluvial depositional environment in the Late-Miocene and Pliocene (Sztanó et al., 2013), which resulted in limited lateral and vertical extension of the sandy reservoir. The influence of aquifer architecture on efficient geothermal use has been also highlighted by e.g. Crooijmans et al. (2016) and Willems et al. (2017). The unfavourable aquifer architecture in our case can negatively affect the reservoir performance.

By plotting the vertical length and the flow rate of each screen (measured during the productivity test), a correlation between the thickness of the sections and the productivity (flow rate) can be observed: The two thickest sections provide the two highest, and

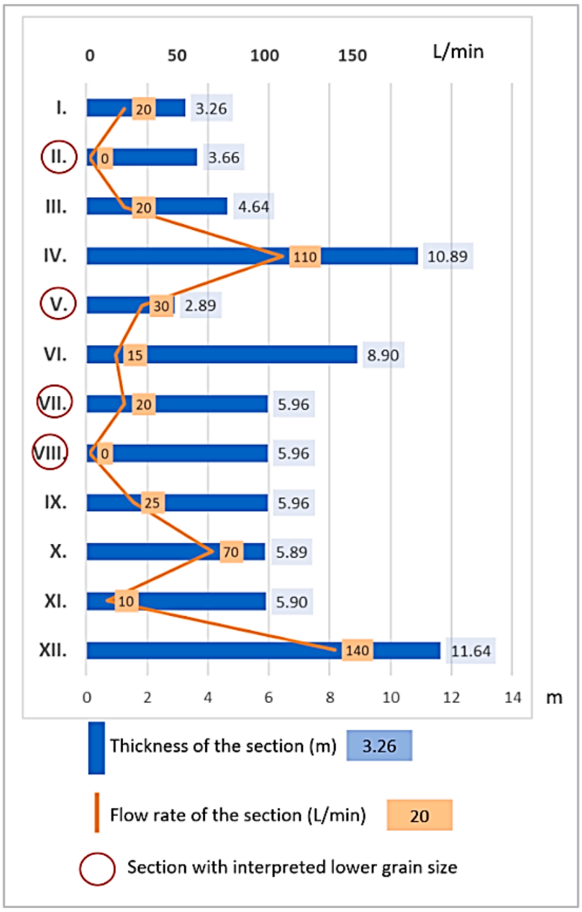

Fig. 7. Length (blue) and low rates (orange line) of the sections.

Table 7
Parameters of the screened well sections in the reference and the study injector wells

	Mezőberény	Orosháza		Hódmezővásárhely			Szeged			Kistelek
	K-116	B-776	B-775	B-1077	B-1094	B-1103	B-744	B-745	B-746	K-49
Total length (m)	75.55	54.00	43.00	81.50	79.12	89.75	127.00	64.00	59.00	61.40
Average length (m)	6.29	13.50	8.60	11.64	15.82	14.96	25.40	21.33	14.75	20.47
Maximum length (m)	11.6	17	17	19	28.76	20.35	50	29	36	29.3

together 50% of the flow rate (IV, XII – Fig. 7). A correlation with the grain size distribution (derived from the gamma log) shows that four sections with low grain size (II, V, VII, VIII) provided relatively low or negligible inflow (marked with red circle in Fig. 7). Based on the assumption that production capacity also indicates the injectivity performance, the segments with low productivity also have a low injection capacity, reducing the total injectivity. Studies at other sedimentary geothermal sites even show the possibility of high productivity and low injectivity in the same well (Brehme et al., 2018).

Rockel et al. (1997) and Seibt and Kellner (2003) proposed an orienting minimum value for permeability (k): $k>5*10^{-13}$ m^2 for an efficient injection into the aquifer. The permeability of the screened sections in the injector in Mezőberény ($8.79*10^{-14}$ m^2 – derived from pressure buildup test) is almost one magnitude smaller than the proposed value. Furthermore, permeability and consequently the transmissivity as well as the specific well capacity is relatively low compared to similar reinjection sites (Markó, 2020). Transmissivity at reference injectors varies between $8.81*10^{-5}$ m^2/s and $1.262*10^{-2}$ m^2/s; out of seven, six values exceed the one of Mezőberény ($1.259*10^{-4} m^2/s$). Similarly, in case of the productivity index only one of the reference injectors shows lower capacity, values range between 1,321 m^3/day/MPa and 19,598 m^3/day/MPa, while at the study site it is 1,707 m^3/day/MPa (Table 8) (Markó, 2020).

In summary, all these values indicate a generally low reservoir performance at Mezőberény.

The small reservoir volume and low transmissivity in Mezőberény are reasons for an inappropriate reservoir performance which can cause a low overall injection capacity. An initial low reservoir performance is a less often documented problem in Hungary; as shown by Markó (2020). Based on that study, most of the reference sites started the operation with much better initial reservoir properties (i.e., transmissivity and capacity).

6.3. *Interpretation of the clogging processes at a local scale*

Clogging processes were interpreted with respect to fines migration, scaling of minerals and organic activity.

Since literature sources (Kovács et al., 2015; Szanyi et al., 2015; Willems et al., 2021) suggest a weak cementation and consolidation as well as poorly sorted grain size of the reservoir formation, release of fine particles (silt, clay) can be expected during fluid flow. Based on core-flood tests, chlorite, kaolinite, illite are the predominantly mobilised minerals which cause formation damage (You et al., 2019). Since the mineral composition of the reservoir formation involves chlorite and kaolinite, risk of formation damage is generally to be expected in this formation. In the injector, screened sections containing low grain size rocks were found using the well logs. Therefore, the possibility of fine particle release is higher within the injection well compared to the production well. At the same time, the ability of the low grain size sections to filter the fines might be also bigger, due to the smaller pore throats. The surface filters on the injection side should be able to filter out the suspended solids having a grainsize of sand and coarse to medium silts. However, due to its bigger mesh size it is unable to filter fine silt and clay size grains, thus they can be reinjected. Their release from the reservoir rock within the injector is also possible, as well as their inflow into the screened reservoir sections. To conclude, the risk of fines release and trapping in the reservoir pores is present. To quantify the amount and specific grain size of suspended fines, on site targeted sampling and analysis are necessary in the future, particulate (suspended solids) content and turbidity of injected and produced waters should be routinely monitored. Installing in line filters, sediment traps or cyclones in the pipeline can prevent the migration of them.

A detailed analysis, using hydrogeochemical modelling and laboratory analysis, showed the type of precipitating minerals in the study system: precipitation of goethite and calcite were both predicted in the model and then confirmed by sample analysis, which underlines the possibility of carbonates, iron and manganese minerals to really precipitate. Comparing the model outcomes to reference reinjection sites with a similar model set-up, both the saturation indices and the amount of scales are higher in Mezőberény than in reference reinjection sites (Table 9) (Markó et al., 2021a; Markó, 2020).

The main reason for precipitation was found in the fluid composition: in case of the Mezőberény wells, dissolved solids (HCO_3^-, Na^+, Ca^{2+}, Fe^{2+}) are higher compared to the other systems (Markó et al., 2021a; Markó, 2020). Formation of predominantly carbonate scaling has been observed at several geothermal sites in the Great Hungarian Plain (Boch et al., 2016). The increased scaling potential is likely caused by fluid-rock interaction in the shallow-water Pannonian aquifers that contains significant amount of carbonate grains (Varga et al., 2019). The dissolved calcium and bicarbonate ions contribute to precipitation due to drop of pressure during production in Mezőberény as well. Another reason is probably the fluid-air contact in buffer tanks at the surface that enhances the precipitation of iron and manganese minerals (Markó et al., 2021a). Due to the contact of water with oxygen the iron in the water will immediately form ferric oxyhydroxide flocs leading to serious mineral clogging problems because of their gelatinous consistency and low density. Consequently, precipitating scales are assumed to be one main reason for clogging.

Considering the biological processes and the organic activity, the dropping temperature along the geothermal cycle optimizes the conditions for mesophilic microbes. The geothermal plant being slightly above the optimum temperature of 20-40 °C (Taylor and Vaisman, 2010)) can slow down their growth. Regarding the pH state, fluids provide beneficial conditions for neutrophil groups. A contact with air/oxygen occurring at the buffer tanks again enhances the activity of aerobic microbes, although many of the detected bacteria are anaerobic. In respect to the organic nutrition sources, the Na–HCO_3-type waters in the Pannonian Basin can contain large amounts of dissolved organic matter (Varsányi and Ó.Kovács, 2009). Likewise, in case of Mezőberény the produced fluid contains a great amount of TOC, phenol, BTEX and PAH. Their content is equally high or even two times higher compared to similar reinjection system suffering from organic clogging (SE Hungary, Hódmezővásárhely – (Osvald et al., 2017)). The presence of these components can determine the microbial flora (Osvald et al., 2017). They provide nutrition for the microbes degrading them, among others for phenol degrading *Pseudomonas* and BTEX degrading *Dechloromonas* species, thus facilitates their overgrowth. Therefore, high microbial activity can be expected. Among the detected groups, sulphate reducing bacteria and methanogenic archaea were identified which are biofilm forming microorganisms: *Desulfobulbus, Desulfotomaculum, Methoanosarcina barkeri.* These microbes as well as *Pseudomonas* form biofilm, which then results in clogging. Additionally, since there are methanogene microbes (Methanosarcina, Methanospirilum) among the detected groups, it can be assumed that the methane content of the fluid is partly produced biologically.

The clogging processes observed at the Mezőberény site detailed

Table 8
Transmissivity and specific capacity of the reference injector and the study injector

	Mezőberény	Orosháza	Hódmezővásárhely		Szeged			Kistelek
	K-116	B-776	K-775	B-1103	B-744	B-745	B-746	K-49
Transmissivity (m^2/s)	1.26E-04	1.91E-03	1.23E-03	1.26E-02	1.37E-03	8.81E-05	3.81E-04	4.52E-03
Specific capacity (m^3/day/MPa)	1707		9532	19598	1321	4685.76	3184	17775

Table 9
Saturation indices (SI) of the analysed minerals in the reference and the study system

	Calcite	Dolomite	Aragonite	Goethite	Hematite	Hausmannite	Manganite	Pyrolusite	Barite	Amorphous silica
Mezőberény	0.54	1.07	0.42	8.78	19.71	3.43	-0.79	4.84	-0.93	-0.43
Hódmezővásárhely	-0.35	-0.62	-0.49	7.97	17.96	-	-	-	-1.07	-0.40
Orosháza	0.11	-1.33	-0.02	7.24	16.60	-	-	-	-1.17	-0.43
Kistelek	-0.85	-1.76	-0.98	7.53	17.16	-2.04	-1.25	3.54	-3.02	-0.5
Szeged	0.00	0.02	-0.13	6.94	15.99	-0.26	-0.99	3.92	-1.84	-1.49

above are typical mechanisms in sedimentary aquifers (e.g., Seibt and Kellner, 2003; Ungemach, 2003; Brehme et al., 2018). In case of the study site, they show a high significance and are likely reasons for the injectivity decline through clogging of the flow pathways.

6.4. Interaction of the different problem sources

On top of the individual problem sources of low injectivity, the interaction of different problems can trigger or even enhance each other: A fundamental interaction process is the impairment of the reservoir performance by the local clogging effects. Accordingly, an initially sufficient reservoir (i.e., with presumably high transmissivity) can be significantly damaged through a clogged near wellbore zone, or the insufficient performance can be fully destructed by clogging. Vice versa the reservoir properties can also determine the clogging processes: the release of formation fines – which can contribute to clogging – originates from the poor cementation, low strength and high clay content of the reservoir rock. Similarly, fluid-rock interaction in an e.g. carbonate rich formation can lead to elevated carbonate-scaling potential at the surface. Another important interaction is expected between the microbial activity and the mineral precipitation. Certain microbes (e.g., sulphate-reducing bacteria) contribute both to biofouling/corrosion and biomineralization (Sand, 2003; Lerm et al., 2013). Therefore, especially mitigating the microbial activity could help reducing the scaling potential. Additionally, regional overpressure can transport deep-origin water to the produced close-to hydrostatic systems. The change of produced fluid-composition also can cause precipitation and clogging due to changed physicochemical conditions.

6.5. Discussion of the workflow

The presented workflow allowed to analyse various problem sources ranging from regional to local scale. The concept presents good practices of problem analysis in a structured form. The integrated approach contributes to a more detailed investigation of the interaction of the separate problems, which helps to reveal the triggering or enhancing effects as well. The presented approach should be used as a guide towards a structured analysis of geothermal reinjection problems moreover it can be applied for prognosis as well.

The workflow can provide background for the analysis of problems at different scales. Problems on the local and reservoir scale are often covered by studies in the literature. However, during geothermal exploration and risk analysis especially regional hydraulic conditions are often neglected. They are not taken into account as part of injection capacity estimation, therefore our workflow highlights their importance. Pressure conditions are usually not taken into consideration in other extensive investigations on reinjection sites suffering from low injectivity (e.g. Klapeida geothermal site – Brehme et al., 2018) though they can play a significant role.

7. Summary and conclusion

Numerous geothermal reinjection sites in porous sandstone aquifers face injection problems during their operation. In this paper, we briefly summarized the different reasons and proposed a complex workflow with different approaches to completely understand and thus be able to prevent the problems. In the presented workflow, potential injectivity declining problem sources are considered ranging them from regional to local scale, covering the hydraulic conditions, the reservoir properties and local clogging processes. In more detail, the proposed approaches cover the investigation of the pressure conditions by defining the pressure regime and the vertical pressure gradient; the evaluation of the reservoir properties by determining the reservoir extension and the reservoir performance; as well as the examination of the processes that can produce plugging materials: physical = particle migration, chemical = mineral precipitation and corrosion, and biological = biofilm formation.

To illustrate the ability of the workflow we performed a complete problem analysis at a geothermal doublet system (Mezőberény - Pannonian Basin) suffering from low injectivity. The outcomes obtained enable the following conclusions to be drawn: Low injectivity at the study site originates from several separate problem sources and their interaction.

A fundamental reason for the low injectivity originates from the local geology: the reservoir volume is likely not sufficient, caused by the limited extension of sandstone bodies both horizontally and vertically. The total vertical thickness of the reservoir is again decreased by inactive segments. The activity of the layers is likely influenced by the low vertical length of certain screened sections and by their fine grain size indicated in the gamma-ray log. Fine grain size is a reason for the low permeability, thus the low transmissivity ($T=1.26*10^{-4}$ m^2/s) of the sections. Transmissivity is reduced to a critical level through plugged pore throats and well screens because of the clogging by suspended solids.

Also, mineral scaling and biofilm formation can contribute to clogging. In this research, precipitation of carbonates, iron and manganese minerals were predicted through hydrogeochemical modelling with a magnitude of 10^{-4}-10^{-5} mol/L; supported by XRD analysis on the precipitated material and confirmed the presence of calcite and goethite. The main reason for the scaling is the fluid composition and salinity. The fluid composition supports the microbial activity as well, as the produced fluid involves particularly high amount of TOC and certain organic compounds (BTEX, phenol, PAH). Microbial products are created by the several biofilm-forming (e.g. sulphate-reducing) microorganisms detected in the water. Sulphate-reducing bacteria can also contribute to the (bio)precipitation and corrosion through interaction with chemical processes. Risk of fines migration is present due to the bad classification and the low strength of the siliciclastic reservoir rocks and the low grain size sections behind the injector screens; but it has not yet been quantified by specific analysis. The filter system that aims to prevent injection of suspended solids, has a too big mesh size to filter the fine particles at the injection site. On the other hand, a drawback caused by regional hydraulics is not expected at the study site, as the pressure regime and vertical pressure gradient are both slightly subhydrostatic in Mezőberény.

In this study, we highlighted the importance of scale-dependence and interaction of the separate potential problem sources. The workflow covers the most dominant injection problems using an integrated concept at different scales. Moreover, it involves regional pressure conditions into the evaluation, which are in most cases not taken into consideration, despite their importance. To conclude, the concept contributes to a risk analysis in exploration and site-development phases towards predicting and preventing injectivity problems. We propose the application of the workflow as a checklist on reinjection sites facing problems with reinjection into a sandstone aquifer. Site-specific analysis can always complete the understanding depending on the local conditions.

CRediT authorship contribution statement

Ábel Markó: Conceptualization, Data curation, Investigation, Methodology, Writing – original draft. **Judit Mádl-Szőnyi:** Conceptualization, Methodology, Funding acquisition, Supervision, Writing – review & editing. **Maren Brehme:** Conceptualization, Methodology, Funding acquisition, Supervision, Writing – review & editing.

Declaration of Competing Interest

The authors declare that they have no known competing financial interests or personal relationships that could have appeared to influence the work reported in this paper.

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