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A Methodology for the Comprehensive Evaluation of the 'Geothermal Reinjection Potential' in Siliciclastic Environments, Demonstrated in the Zala Basin, SW Hungary

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INTRODUCTION

Sustainable thermal water use requires returning the produced fluid into the subsurface. In most cases, without reinjection, the potentiometric level in the aquifer decreases as well as compaction and land subsidence may occur (Allis, 2000; Békési, et al., 2022). However, a successful reinjection into siliciclastic aquifers is not straightforward due to the initial geological-hydrogeological conditions and the disturbed physical-chemical equilibrium. Low injectivity has been experienced worldwide, in some cases leading to the shut-down of geothermal systems (Stefansson, 1997; Ungemach, 2003; Kamila, et al., 2020; Song, et al., 2020; Markó et al., 2021; Luo, et al., 2023).The present study aimed at increasing the level of success in geothermal reinjection into siliciclastic aquifers in general, as well as providing new results for Hungarian sedimentary basins.

1 THE GEOTHERMAL REINJECTION POTENTIAL

During geothermal reconnaissance studies, a variety of potential assessments are carried out, including an evaluation of temperature and reservoir conditions and the amount of energy that can be extracted (Stefansson, 2005; Rybach, 2015; Nádor, et al., 2019). Since the use of thermal water can be considered sustainable only if the water is replenished by reinjection, similar to how the geothermal potential is assessed prior to the exploitation of an area, this study proposes that the "geothermal reinjection potential" should also be assessed in advance of geothermal field developments (Markó, et al., 2024, Markó, 2025).

In this study, the "geothermal reinjection potential" is defined as the geological probability of success of reinjection (POS[RI]), namely, the probability that reinjection will be successful from a geological point of view. The key point of the assessment is the investigation of the potential risk factors on different scales, namely the problem sources potentially hindering reinjection. In this regard, solely the geological-hydrogeological factors are considered for the evaluation, the technical, engineering and financial details of transforming wells are out of scope of this study.

2 METDHODS & RESULTS

2.1 Methods

For the evaluation of geological risk factors we set up a multiscale scientific workflow which provides specific approaches and methods to tackle the potential risk factors (c.f. Markó, 2025): i) the regional scale with the hydraulic conditions (elevated hydraulic head and upward flow); ii) the reservoir scale with reservoir properties (limited aquifer presence or extension, high heterogeneity, low reservoir permeability and performance); and iii) the local scale with potential physical, chemical and biological clogging processes (particle migration, mineral precipitation and corrosion, biofilm formation).

These risk factors are evaluated in separate scientific analyses, to assess their significance, and contribution in a possible low injectivity. In other words, the geological probability of success (POS[G]) of the factors is estimated (1).

$$\mathrm{POS[G]} = 1 - \mathrm{Risk[G]} \quad (1)$$

The proposed evaluation of the geothermal reinjection potential follows and fits into a recently introduced geological risk assessment methodology. For the quantification, a modified chance adequacy matrix was created and applied (see in Figure 2) to quantify the geological probability based on the supportiveness of the information (i.e. how the data supports the assumption that the reinjection is successful from a geological point

of view), and the knowledge/confidence (i.e. the amount and quality of the data available). This way a value between 0 and 1 is assigned to each factor in respect to their likelihood of occurrence.

Taken the assumed independency of the factors and their probabilities, the overall geological probability of successful reinjection is obtained by multiplication (1):

$$\mathrm{POS[RI]} = \mathrm{POS[H]} \times \mathrm{POS[A]} \times \mathrm{POS[C]} \quad (1)$$

Here, POS[H] represents the hydraulic conditions – at the regional scale, POS[A] represents the aquifer properties – at the reservoir scale, and POS[C] evaluates the clogging processes – at the local scale. POS[RI] thus evaluates the success of injection by analysing the separate problem sources as described in the workflow.

2.2 Results

Demonstration of the methodology was carried out for the Barlahida demonstration area, situated in the Zala Basin, south-west Hungary. Here, siliciclastic shallow-water Pannonian sediments (deltaic Újfalu and alluvial Zagyva formations) represent the basin fill and the main thermal water bearing aquifer units (Fodor et al. 2013). Thermal water is widely utilised – mostly for balneological purposes – however, reinjection is far behind the necessities with only one installed reinjection system.

Outcomes of the analysis of three main risk factors are summarized in Table 1. Assignment of POS values are carried out using the modified Chance Adequacy Matrix shown in Figure 1.

Table 1. Results of the evaluation for an example Barlahida-Pusztaszentlászló location (light blue star on Figure 2 map) within the demonstration area

Aspect	Evidence and supporting information	Evaluation
Regional hydraulics (H)	Potentiometric maps, pressure-elevation profile: (vertical pressure gradient: 9.41 MPa/km), hydraulic head-elevation bulk profile.	Hydraulic head values indicate hydrostatic pressure with a subhydrostatic gradient being favorable for low pressure reinjection → POS[H]= 0.99
Aquifer properties (A)	Average permeability based on well-tests in other thermal water wells: $8.39*10^{-13}$ m^2 with relatively high value of 521 mD from thermal well nearby. Good quality 3D seismic was used: identified volume at RMS amplitude map as sandstone body.	Sandstone body with sufficient volume were detected at the location, permeability is likely favourable, production-injection doublet with good hydraulic connectivity can be placed with high probability →POS[A]= 0.95
Clogging processes (C)	Experience from analogue systems. Hydrogeochemical datasets and modelling suggests long time (>100 years) of 50% plugging of the pore space in the near well-bore zone.	Kown risk of pore clogging. Low risk of chemical clogging. Lack of detailed investigations and specific datasets for microbial and physical clogging, →POS[AQ]= 0.5

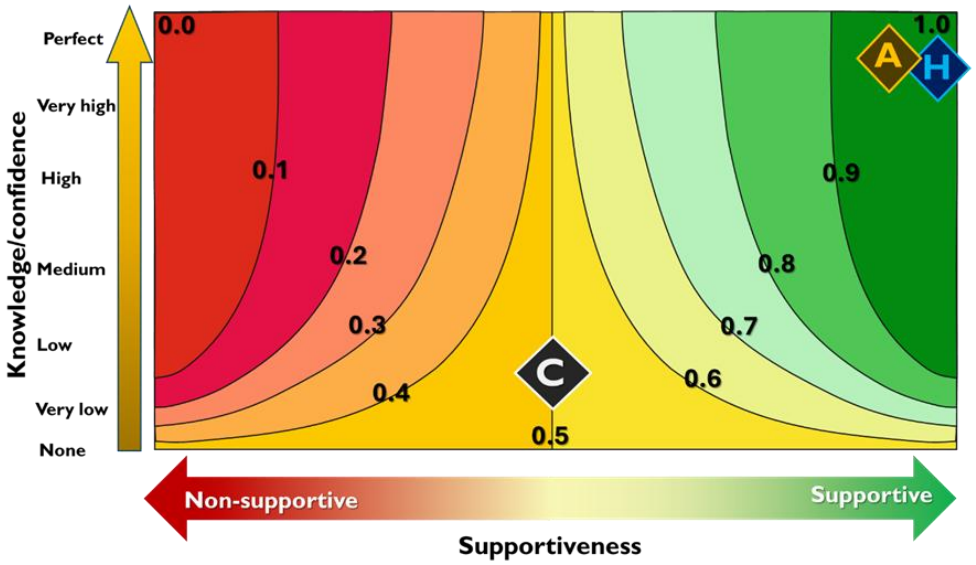


Figure 1. Modified chance adequacy matrix for the evaluation of the risk factors at Pusztaszentlászló-Barlahida (light blue star on Figure 2) location. Capital letters indicate the POS values: hydraulics with very high knowledge/confidence and supportive data is assigned with POS[H]=0.99; aquifer properties with supportive data and very high-perfect knowledge/confidence is assigned with POS[A]=0.95; clogging processes with low very low knowledge-confidence was assigned with POS[C]=0.5

The quantified geological probability of success values are multiplied, resulting in a POS[RI] = 0.47 (3)

$$\mathrm{POS[RI]} = \mathrm{POS[H(0.99)]} \times \mathrm{POS[A(0.95)]} \times \mathrm{POS[C(0.5)]} = 0.47 = 47\,\%. \quad (3)$$

The outcome of the quantification can be used to compare various locations, as well as input for creating reinjection potential maps for a target area, to find the best location to reinject.

3 DISCUSSION AND CONCLUSIONS

3.1 Reinjection potential map

Following the example location of Barlahida-Pusztaszentlászló, example reinjection potential maps were created for the area of the investigated 3D seismic block within the 700-1200 m depth interval (Figure 2). POS[H] map represent the whole area with a 0.99 value, since hydraulic conditions were assessed to be favourable. POS[A] indicates variations: at the margin of the identified sandstone bodies a 0.85 value is assigned, while in the middle 0.95 value is assigned; regions without identified sandstone bodies are represented by POS[A]=0.1. POS[C] is generally characterized by 0.5 due to the limited knowledge. The outcome is the map of POS[RI], with the most prospective areas having POS[RI]=0.47.

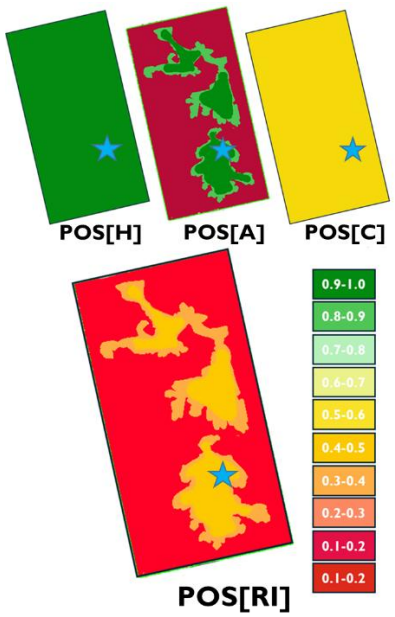


Figure 2. Geothermal reinjection potential map for the 700-1200 m depth interval of the area of the Barlahida. Colours represent the POS[RI] which is the qualitative measure of reinjection potential (modified from Markó (2025)).

3.2 Flow chart of the methodology

A flow chart of the application (Figure 3.) guides the analysis presented in this study. A multiscale scientific analysis using the workflow is carried out scale by scale to characterize the Hydraulic conditions, Aquifer properties, and Clogging processes. Then, using the Risk analysis scheme, risk and probability of success values are quantified for hydraulics (POS[H]), aquifer (POS[A)] and clogging (POS[C]). Combining the POS values, POS[RI] is calculated. Then, the Reinjection potential map can be produced for specific area and depth interval. Finally, decision can be made where to install reinjection wells and production-reinjection doublets.

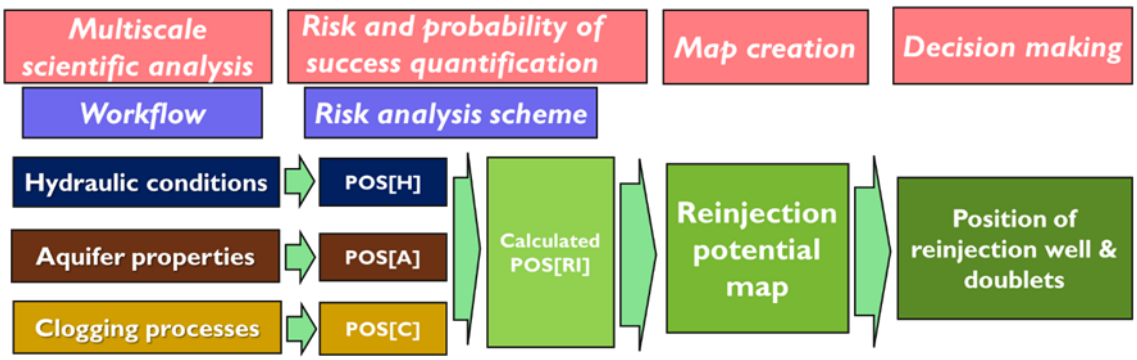


Figure 3. Flow chart of the methodology presented in the study (Markó, 2025)

3.3 Applicability, outlook

The main message of the study and the presented methodology is that understanding and mitigating the reinjection-related risks and problems requires commitment, time, human capacity and financial investments. All the available knowledge and all the existing datasets should be utilised and complemented with novel measurements, analyses, and systematic (re)interpretation. The presented workflow and approaches are not the ultimate solutions for solving reinjection related problems; further approaches, site-specific methods should be also involved. Nevertheless, the introduced methodology can contribute to more successful reinjection attempts in case of porous aquifers.

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