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Understanding And Quantifying The Potential Scaling In Geothermal Reservoirs

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ABSTRACT

The use of geothermal energy based on hydrothermal reservoirs is well accepted in Germany. An open-loop system represented by a geothermal doublet (injection and production wells) is the typical technological choice. The aim is to extract the heat stored in geothermal fluids. A geothermal fluid is produced and after heat withdrawal, it is subsequently reinjected into the reservoir via a second well due to environmental reasons and also to maintain the reservoir pressure. Continuous fluid circulation requires a highly permeable reservoir to ensure flow from the injection well to the production well.

In Germany, there are three suitable regions for (hydrothermal) geothermal use: The Upper Rhine Graben, the North German Basin and the North Alpine Foreland Basin. The reservoir temperature in the multiple aquifer layers is normally higher than 65 °C, which allows direct use for district heating purposes. However, they are subjected to geochemical challenges due to its local minerology. Mineral scaling in geothermal reservoirs is a significant challenge caused by the precipitation of minerals like silica, calcite, and sulfides when geothermal fluids cool and change pressure. This can lead to problems like clogged pipes, reduced heat exchanger efficiency, and lower system performance. Management strategies include using chemical inhibitors, mechanical cleaning, and engineering solutions like fluid mixing control to mitigate scale formation. Scaling is a common and widespread challenge known from numerous deep geothermal projects, particularly linked to highly saline brines encountered in the North German Basin and the Upper Rhine Graben (Haas-Nüesch et al., 2018). There is a large diversity of oversaturated minerals under operational conditions leading to scaling. Most common groups are carbonates, silica, and sulphides. Scalings can substantially affect the geothermal energy productivity index by reducing heat transfer and by physically clogging pipe systems. They have to be removed regularly, resulting in additional operation costs and downtimes of the plant.

Upper Jurassic carbonates – also known as the Malm reservoir – lie beneath the North Alpine Foreland Basin and constitutes one of the most productive hydrothermal reservoirs in middle Europe. The Malm reservoir classifies as a fractured and karstified aquifer crossed by numerous normal faults, which generally results in high flow rates and can reach a thickness of up to 600 m. However, the water-rock interaction is predominantly characterized by calcite- and dolomite-related mineral dissolution and precipitation processes, which makes the reservoir target more prone to the generation of scaling in the installed and future planed geothermal installations.

The numerical finite-element simulator FEFLOW is used to model the subsurface flow and heat transport conditions. The FEFLOW piChem computational framework is used to extend the range of physical and chemical processes being modelled and include the reactive transport mechanisms associated with scaling in deep geothermal reservoirs. One of the most discussed alternatives to minimize the scaling effect is the injection of CO_2 to reduce the pH value nearby the wells. Such a scenario is modelled in this work, considering the geothermal doublet. This helps us to evaluate whether injected CO_2 produces (or not) unexpected side effects on the production well (e.g. permeability decrease – reservoir damage). Here, we present our most recent simulation results.

1 INTRODUCTION

The optimization of geothermal energy production involves multiple interrelated factors, each exerting a varying degree of influence on the overall efficiency of the energy system. In particular, geothermal fluids generally contain dissolved gases and solids whose thermodynamic behaviour during the utilization cycle may cause trouble either by attacking the metal surfaces (corrosion) or causing scaling (e.g., Stober & Bucher 2021; Sharmin

et al. 2023; Penot et al. 2023; Bowman et al. 2023). Mineral scaling represents a significant challenge in the sustainable exploitation of geothermal resources. The predominant types of scale deposits are commonly categorized into four major groups: silica and silicate compounds, carbonates, sulphates, and sulphides (e.g., Corsi 1986; Stáhl et al. 2000; Zhao et al. 2023).

Numerous studies have quantified scaling and corrosion phenomena in geothermal installations, while field observations from various geothermal projects worldwide have documented mineral dissolution and precipitation processes occurring in the vicinity of injection and production wells but also overall in the geothermal system (e.g., Alt-Epping et al. 2013; Wanner et al. 2014; Lippmann et al. 1991). On the one hand, Baumann et al. (2017) summarized observations made of improved injectivity at the Pullach geothermal well (TH3) targeting the Upper Jurassic aquifer in the North Alpine Foreland Basin (NAFB) while Kühn et al. (2002) predicted dissolution of anhydrite in the vicinity of the injection well in Detfurth sandstones (Bundsandstein) at Stralsund, Germany. Similar observations as the ones made for the Pullach geothermal sit have been corroborated in many other geothermal sites targeting the Upper Jurassic fractured and karstified carbonates in the NAFB and are attributed to dissolution of calcite and dolomite near the injection wells. On the other hand, Pátzay et al. 2003; Jarrahian et al. 2024 documented or predicted scaling and corrosion problems in low- and high-enthalpy geothermal wells in Europe.

Increasing academic and industrial interest has been directed toward the development of coupled hydro-chemical and hydrodynamic models that characterize the interactions between minerals and hydrothermal fluids or groundwater under diverse thermodynamic conditions within geothermal reservoirs and installations (e.g. Pandey et al. 2014, Baumann et al. 2017). This growing focus is largely driven by operational challenges, including long-term reservoir degradation as well as the occurrence of scaling and corrosion in geothermal wells, heat exchangers, and surface piping systems.

This study presents a comprehensive quantitative workflow for the numerical modelling and simulation of reactive transport processes, specifically mineral dissolution and precipitation induced by geothermal reservoir operations. Additionally, it introduces numerical models for assessing the potential for scaling and corrosion in geothermal wells and surface piping systems. The modelling framework integrates multiple simulation tools, including the commercial software FEFLOW® and piChem® (developed by DHI WASY), as well as the open-source geochemical code PHREEQC, developed by the U.S. Geological Survey (USGS) (e.g., Appelo & Postma, 2005; Parkhurst & Appelo, 2013). In addition, this study aims to reduce operational risks in geothermal wells by advancing the understanding and quantification of dynamic thermo-hydro-chemical processes within both the reservoir and surface installations. To this end, several typical thermodynamic conditions and published data on mineral compositions of reservoir rocks and geothermal fluids as well as dissolved gases are considered to accurately simulate key mineral dissolution and precipitation reactions during reactive transport, thereby supporting the optimization of the geothermal production cycle through the identification, prediction, and mitigation of critical geochemical interactions. We present in this work preliminary results and our latest stage of development.

2 METHODOLOGY

2.1 Geothermal Reservoir

The modelling area in this study corresponds to the Greater Munich area and is located in the South German Molasse Basin, also considered in the literature as the North Alpine Foreland Basin. It covers an area of around 2,700 km^2 (approx. 57 km x 47 km) (Dussel et al., 2016). The Upper Jurassic (Malm) aquifer is the targeted geothermal reservoir for exploration and development. The aquifer consists mainly of fractured and karstified carbonates and is considered as the most important reservoir for deep geothermal use in Germany (Dussel et al., 2018). The location of the model area can be seen in Figures 1 and 2 as well as the distribution at the country-level scale of the proven and assumed hydrothermal potential with the corresponding temperature range.

The main hydrothermal aquifers relevant for deep geothermal development are encountered in stratigraphic units such as Tertiary, Cretaceous, Upper Jurassic (Malm), Middle Jurassic (Dogger). The Malm aquifer consists of porous, fractured and karstified limestones and dolostones with hydraulic conductivities ranging from 10^{-7} to 10^{-4} m/s (Dussel et al., 2016). The Upper Jurassic geothermal reservoir has a thickness of about 600 m (Meneses Rioseco et al., 2018, and references therein) and reaches temperatures up to 150 °C (Dussel et al., 2016, and references therein). It is important to note that the hydrothermal aquifer falls deeper towards the south-east. Therefore, also the temperature in the reservoir rises towards the south-east. The thermal water in the reservoir is of relatively low total dissolved solid and is classified as Na–Ca–HCO3–Cl type (Birner et al., 2011).

Various carbonate facies are present in the Malm. The Upper Jurassic carbonates show high heterogeneity in facies distribution and thus, reservoir permeability is significantly controlled by facies distribution. Fundamentally, there are two main types of facies. On the one hand, the bedded or basin facies, which consist of bedded limestone, and on the other hand the reef-/mass facies. While reef-/mass facies are the reservoir hydraulic units that allow economic geothermal energy generation, the bedded/basin facies show low hydraulic conductivity and are therefore not suitable for economic geothermal energy production (e.g., Böhm 2012, Dussel et al. 2012).

Although, the stratigraphic unit Purbeck does not belong to the Malm, but rather to the Cretaceous, this unit is also considered as part of the reservoir in this modelling study due to its similar lithology compared to the Upper Malm (Dussel et al., 2016).

The reservoir is crossed by a relatively large number of fault zones, which have been considered as important geothermal targets due to their hydraulic activity. Two major fault systems have been interpreted and mapped, the so-called Munich fault or also named Markt-Schwaben fault. This prominent normal fault has a maximum vertical offset of up to 350 m (Meneses Rioseco et al., 2018).

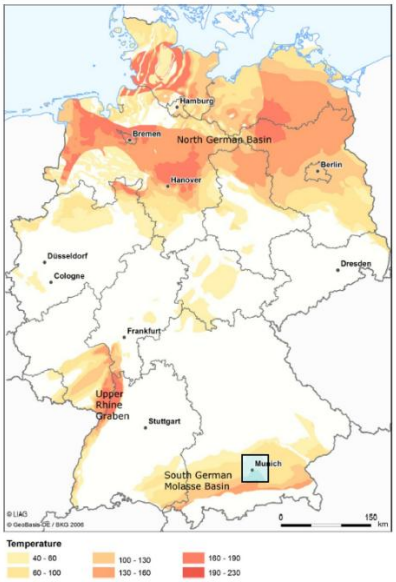


Figure 1. Location of the study area around Munich. Background distribution shows the geothermal potential in Germany displayed in temperature (°C). The modelling domain is shown in the polygon (modified after Dussel et al., 2016, Suchi et al., 2014) (www.geotis.de)

2.2 Previous numerical models of the deep geothermal reservoir

Leibniz Institute for Applied Geophysics (LIAG) is the owner of the FEFLOW numerical model covering the entire reservoir. The LIAG model is built following a fully structured and layered-based three-dimensional mesh based on the FEFLOW Version 6.2. The top of the numerical model corresponds to the top of Lithothamnion limestone, and the model bottom is the top of Dogger/Cristalline. The model contains 25 slices. In FEFLOW®, a slice corresponds to a 3D surface, where two consecutive slices define a numerical layer, which may coincide (or not) with a hydrogeological and/or lithological layer. The different slices reflect both the lithostratigraphic and hydrostratigraphic profiles. The top of the Lithothamnion limestone, top of Purbeck as well as the top of Malm Alpha to Gamma and top of Dogger/Cristalline are considered.

Hydrogeologically, the entire model is divided in three main layers. The top (Lithothamnion limestone) and the bottom (Lower Malm (Malm Alpha to Gamma)) layers are considered as aquitards whereas the middle layer (combining Purbeck and Higher Malm (Malm delta to zeta)) is considered as thermal aquifer (Dussel et al., 2016). The fault zones are implemented vertically in the model and incorporated either as finite elements (buffer zone of 25 m from fault centre) or as discrete feature elements (DFEs). DFEs are two-dimensional elements in a three-dimensional domain and can have their own hydraulic and thermal properties.

Subsequently, the joint research project GRAME is mainly organized by the municipality energy supplier of the city of Munich (Stadtwerke München - SWM) (Meneses Rioseco et al., 2018) provided new insights about the structural and stratigraphic data. The collected 3D seismic data within the GRAME project corresponds mainly

to the southern part of the city of Munich. This region will be referred to in this study as the GRAME region. GRAME is the abbreviation name (in German) of the joint research project at hand and is translated to “Optimized and Sustainable Reservoir Development for Deep Geothermal Projects in the Bavarian Molasse Basin. Development of 400 MW Geothermal Resources for the Munich District Heating”.

The collection of data from a 3D seismic campaign occurred during the winter of 2015/2016 in the southern area of Munich (Meneses Rioseco et al., 2018). The seismically explored area covers an extension of approx. 170 km^2. A new 3D geological model was built with SKUA-GOCAD and includes the geological horizons and the fault system (Ziesch et al. 2018). This structural model has been further reprocessed for reservoir modelling purposes (e.g., Meneses Rioseco et al. 2019). Rivera Villarreyes et al. (2022) presented an update version of the reservoir model by using previous modelling investigations and the update 3D geological structural model. This new model was built with FEFLOW v. 7.5 and included a better representation of fault system by means of tetrahedral fully unstructured meshes, e.g. fault system was not anymore simplified as vertical structures. The main focus of the numerical model was uncertainty quantification of reservoir performance based on possible representations of the reservoir hydro-thermal reservoir parameters.

In the present study, the modelling area is outside the updated region with the new 3D geological structural model. Therefore, the model parametrization follows still the first assumptions implemented in the LIAG’s model.

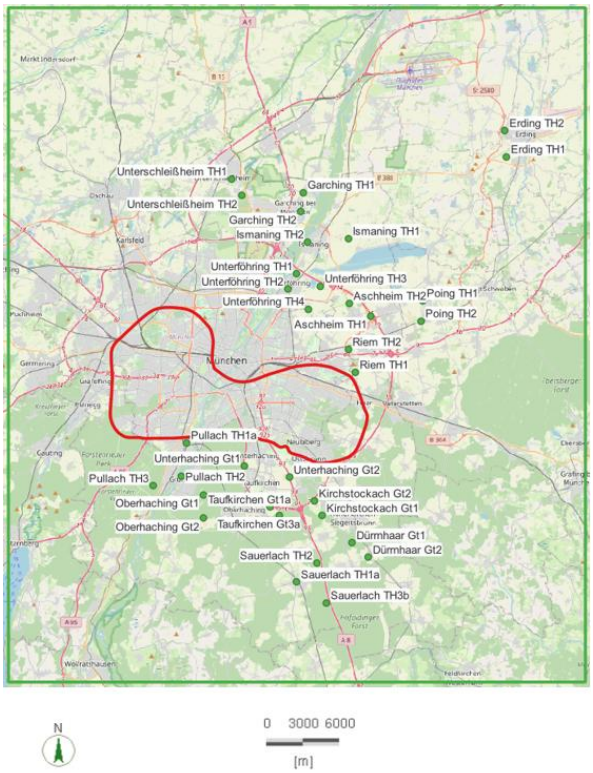


Figure 2. FEFLOW modelling domain (extension of entire image). The region with the new 3D structural geological model (red polygon) and the geothermal installations (until 2015) that are still operating are displayed.

2.3 Three-dimensional groundwater flow and heat transport

FEFLOW (version 10) is chosen as the modelling and simulation tool to solve the relevant, thermo-hydraulic processes in the subsurface. A three-dimensional groundwater flow equation in FEFLOW considers the calculation of the hydraulic head and the Darcy velocities in a single-phase system is described as follows:

$$S_o \frac{\partial h}{\partial t} + \nabla \cdot q = Q \tag{1}$$

$$q = -K \cdot \nabla h \tag{2}$$

where *h* is the hydraulic head [m], *q* is the Darcy velocity [m d^{-1}], *So* is the specific storage coefficient [m^{-1}], *K* is the hydraulic conductivity tensor [m d^{-1}] and *Q* denotes the general sink/source term [$m^3 d^{-1}$]. Both equations [1] and [2] are used to derive the groundwater flow equation as follows (Diersch, 2013):

$$S_o \frac{\partial h}{\partial t} - \nabla \cdot (K \cdot \nabla h) = Q_h + Q_{hw} \tag{3}$$

The heat transport equation considers the assumption that liquid and solid phases of the porous medium are locally in thermodynamic equilibrium. With this assumption, the conservation equation of energy expressed in the convective form (Diersch, 2013) can be derived:

$$(\varepsilon s \rho^f c^f + (1-\varepsilon)\rho^s c^s)\frac{\partial T}{\partial t} + \rho^f c^f q \cdot \nabla T - \nabla \cdot (\Lambda \cdot \nabla \mathrm{T}) = Q_T + Q_{Tw} - \rho^f c^f (T - T_o) Q \tag{4}$$

where ε denotes the porosity [-], *s* stands for the saturation of fluid in the void space (*s*=1 for fully confined conditions) [-], *T* is the computed nodal temperature [°C], T_o is the reference temperature [°C], $\rho^f c^f$ is the volumetric heat capacity of the fluid phase [J m^{-3} K^{-1}], $\rho^s c^s$ is the volumetric heat capacity of the solid phase [J m^{-3} K^{-1}], Λ is the heat thermal conductivity [J m^{-1} d^{-1} K^{-1}] and *Q* is the source/sink term from Eq. [1] in [$m^3 d^{-1}$]. The thermal conductivity is expressed further as follows:

$$\Lambda = \Lambda_o + \Lambda_o^s + \rho^f c^f D_{mech} \tag{5}$$

$$\Lambda_o = \varepsilon s \Lambda \delta \tag{6}$$

$$\Lambda_o^s = (1-\epsilon)\Lambda^s \delta \tag{7}$$

where Λ_o is the isotropic thermal conductivity of the liquid and Λ_o^s is the isotropic thermal conductivity of the solids (Diersch, 2013). The isotropic thermal conductivity for the solid phase is expressed as follows

$$\Lambda_o^s = (1-\epsilon)\Lambda^s \begin{bmatrix} 1 & 0 & 0 \\ 0 & 1 & 0 \\ 0 & 0 & \Lambda_{aniso} \end{bmatrix} \tag{8}$$

$$D_{mech} = \beta_T \|q\| \delta + (\beta_L - \beta_T)\frac{q \otimes q}{\|q\|} \tag{9}$$

where D_{mech} is the physical tensor of mechanical dispersion [m^2 d^{-1}], β_L is the thermal longitudinal dispersivity [m], β_T is the thermal transverse dispersivity [m] and δ is the unit or identity square matrix.

The system of equations is solved by means of the direct solver PARDISO in FEFLOW.

In terms of boundary conditions for the fluid flow, lateral inflow/outflow in the reservoir domain was prevented by imposing a Dirichlet boundary value of 0 m. Flow movement could only happen by means of the source/sink terms used to prescribe the geothermal installations (production and injection wells). The heat transport equation was solved using Dirichlet Temperature boundaries at the top and bottom surfaces of the reservoir. Further details of the heat-transport boundary conditions are discussed in Dussel, et al. (2016).

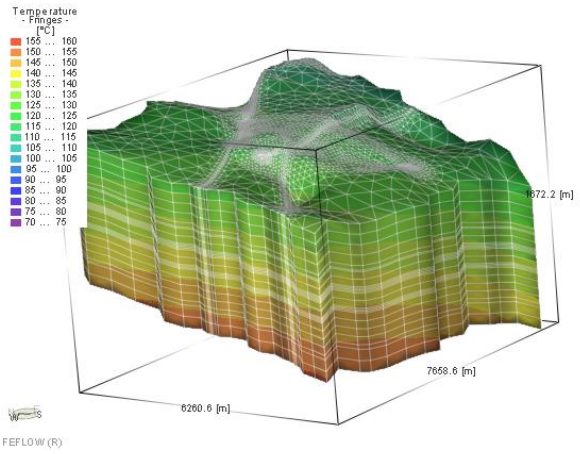


Figure 3. Distribution of initial temperature in the 3D FEFLOW model.

The numerical model covered an operation period of the geothermal installations of 48 years. The simulation started in the year 2014. The automatic time-stepping approach in FEFLOW is used and combined with a Forward Euler/backward Euler (FE/BE) predictor-corrector approach.

2.4 Geochemical modelling

Currently, FEFLOW model of the reservoir includes only flow and heat model processes (Dussel, et al. 2016). A small region was extracted to implement the mass transport and geochemical reactions in FEFLOW. The extension covers an area of approximately 6.2 km x 7.6 km. The main motivation to reduce the modelling size is to minimize the numerical effect involved in the reactive transport. The area chosen for the modelling included the geothermal boreholes Th1a, Th2 and Th3b. The system consists of a geothermal triplet with two injection wells Th2 and Th3b, and one production well Th1a (see Figure 2). The injection temperature was constant to a value of 45ºC for the entire modelling period. The fluid rate was considered 6307.2 m^3/d and 4060.80 m^3/d for the wells Th2 and Th3b, respectively. The production flow rate was equal to the sum of both injection wells. This configuration assures potentially the preservation of the fluid pressure in the reservoir.

The reason of the area selection for the geochemical modelling is purely practical, since chemical information of the water quality is required for the analysis. The present study uses as reference the values reported by Baumann et al. (2017).

The standard mass transport equation including advective, diffusive and dispersive terms was solved in FEFLOW. Further details are available in Diersch (2013). The geochemistry was solved by using FEFLOW piChem module. The module offers a coupling between PHREEQC (reactive transport) and FEFLOW (flow, mass and heat transport). The coupling of geochemistry and hydrology in piChem assumes that aqueous phase flow, be it fully saturated or variably saturated, can be expressed as the transport of the individual components that constitute the aqueous phase. The split-operator scheme decouples the simultaneous and dependent processes of solute transport and geochemical reactions into independent, sequentially solved calculation steps. piChem employs a non-iterative sequential approach (SNIA) for operator splitting with user-defined splitting time steps Δt. At every reaction step, the solution composition in terms of ion species is reconstructed from the transported element assembly and the charge balance before it is speciated with the solid and gaseous phases. After the reaction step, the transport equations are updated with the resulting element concentrations in the aqueous phase. Further details are available in the FEFLOW piChem user manual.

Table 1. Hydrochemical composition of wells TH1a and Th2 extracted from Baumann et al. (2017).

	Th1a			Th2
	2005	2006-2012		2004
		Mean	Std. dev	
pH	6.42	6.67	0.36	6.52
Na^+	6.59	10.4	0.66	20.05
K^+	1.16	0.83	0.06	2.48
Mg^{2+}	3.17	0.21	0.022	1.83
Ca^{2+}	16.56	1.10	0.11	6.94
Cl-	23.55	7.53	0.60	24.58
SO_4^{2-}	0.35	0.30	0.082	1.36
HCO_3^-	4.80	5.7	0.43	5.35

The geochemical model was represented following the PHREEQC convection. Equilibrium phases considered CH_4 (g), CO_2 (g), O_2 (g) and N_2 (g). The chemical components of the solution were the ones measured at Th2 and presented in Baumann et al. (2017).

3 RESULTS AND DISCUSSION

In a first model run, we considered only flow and heat transport to verify the results of the reduced model domain with the large (reservoir-scale) model. The values of the modelled temperature distribution between Th1a and Th2 are shown in Figure 2 for the years 2014 and 2061. The propagation of the cold plume (45 °C injection temperature) is shown in both cross-sections.

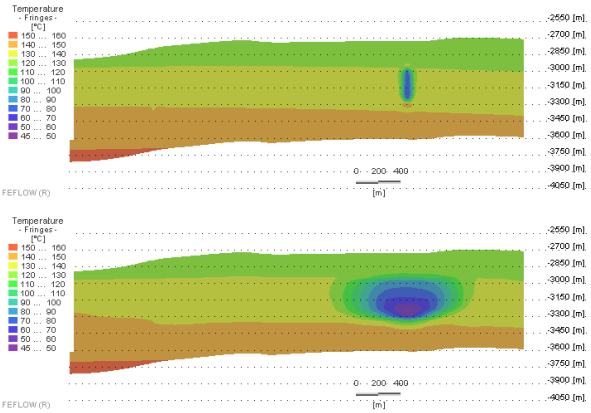


Figure 4. Simulated temperature distribution between wells TH1 and TH2 estimated in January 2014 (upper figure) and December 2061 (lower figure).

The measured hydrochemical data at Th2 (Baumann et al. 2017) was used to run PHREEQC in inverse mode. The idea was to identify the possible equilibrium phases and relevant processes for the geochemical representation of reservoir. Our geochemical results in PHREEQC are in well agreement with those values modelled by Baumann et al., 2017 (Table 2). The minimal discrepancy between both modelling cases could be associated to the present of the equilibrium phase ethane, which was not used in our case, since it is not part of the standard PHREEQC database file and this would have required certain adaptations.

Using the results of the PHREEQC modelling at Th2, we modelled the saturation index (SI) for three major minerals (Calcite, Dolomite and Gypsum) as well as the pH value. The temperature range for the reactions was considered from 0° up to 200 °C assuring the expected temperature range at the reservoir is covered (see Figure 1). These results are presented in Figure 3. A positive mineral saturation index indicates that a solution is supersaturated with respect to a particular mineral, meaning it contains more dissolved ions than would be present at equilibrium. This suggests a tendency for a specific mineral to precipitate out of solution, potentially forming scale or deposits. For example, PHREEQC simulation indicated that a potential precipitation of calcite with temperature above approximately 70 °C. In the case of dolomite, its saturation index increases drastically from temperature above approximately 80-90°C. Based on the Th2 geochemical conditions is not expected a precipitation due to gypsum.

Table 2. Hydrochemical characterization at Th2: Measured and simulated values (Baumann et al., 2017) vs. simulated in the present study.

	Measured (mmol/L)	Simulated (mmol/L)	
	Baumann	Baumann	Ours
Na	17.16	11.11	14.57
K	0.94	0.85	0.8
Mg	0.83	0.88	0.7
Ca	1.95	1.82	1.66
Cl	15.54	8.20	13.19
Br	0.03	0.00	0.03
S	1.01	0.61	0.86
HCO_3	8.19	8.29	8.95

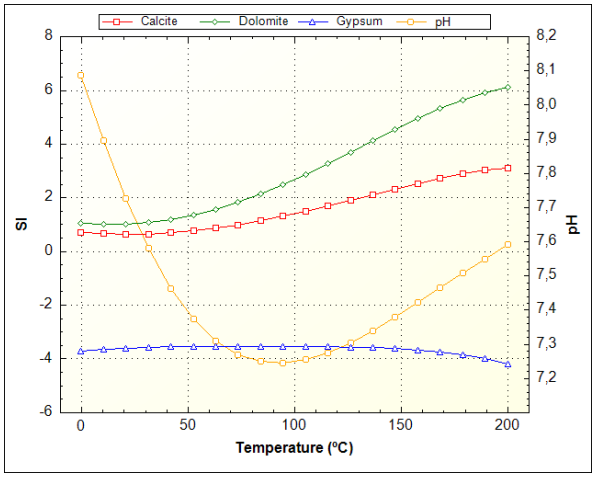


Figure 5. Estimated values of saturation index (SI) and pH for different minerals in the reservoir over a temperature range from 0 to 200 °C.

The modelled amount of Ca in mmol/kgw for a temperature range from 0°C up to 200°C is shown in Figure 4.

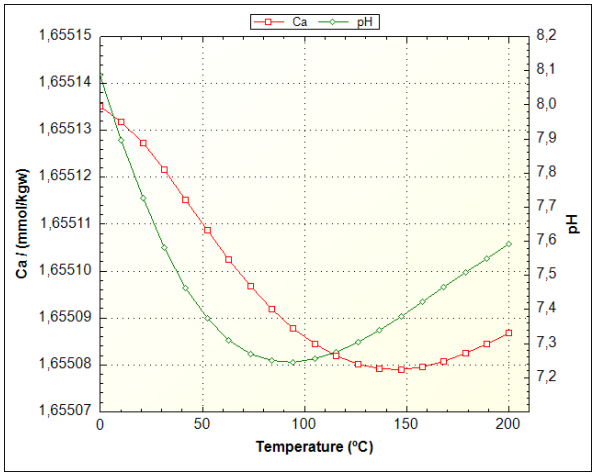


Figure 6. Estimated values of Ca (mmol/kgw) and pH for temperature range from 0 to 200 °C.

In FEFLOW, the geochemical model considered the solution previously identified with the inverse modelling at Th2. We assumed that the reservoir and the injected water via Th2 and Th3b wells have the same quality. All this was modelled using FEFLOW piChem model. In parallel, conservative mass transport was also modelled to verify that the numerical solution is free of instabilities and oscillations.

The results of the mass transport (conservative) are shown in Figure 5. The mass front derived from the injection wells Th2 and Th3b after 14 years did not reach the production well Th1a. Such as results can be verified with the heat transport modelling (Figure 6). Here we can the cold plume originated by the injected water with 45°C does not reach neither the production well.

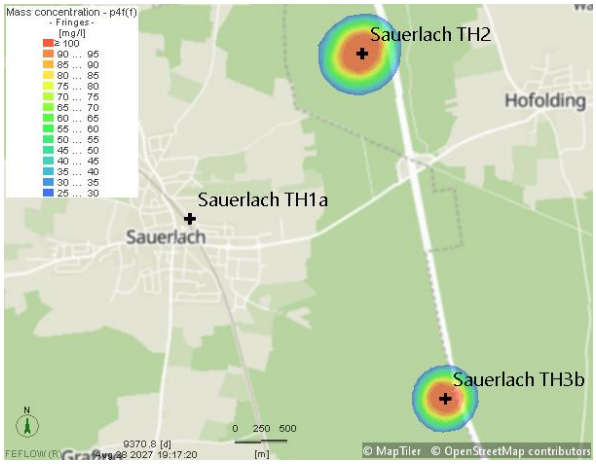


Figure 7. Simulated conservative tracer: Injection took place into wells TH2 and TH3b. Concentration distribution is after approximately 14 years of continuous injection.

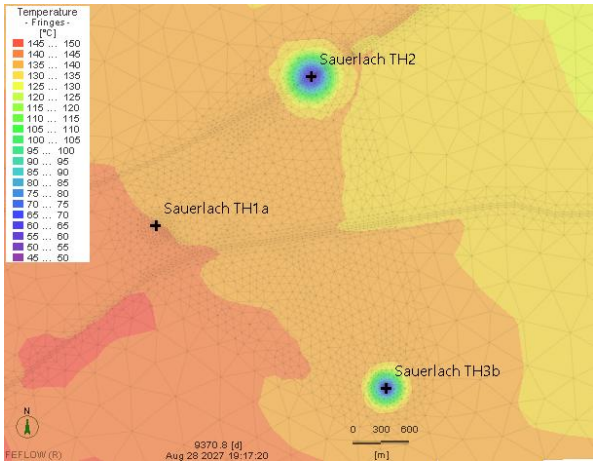


Figure 8. Simulated reservoir temperature (°C) near the geothermal system after 14 years.

Based on preliminary results of the reactive transport modelling, Ca concentrations varied from 20.8 mg/L to 100 mg/L in the entire model domain after 14 years of simulation. In the case of Na, concentrations fluctuated from 100 mg/L to 452 mg/L. The distributions of Ca and Na at the location (depth) of the injection wells are shown in Figures 7 and 8. Based on these modelling results, the estimated saturation index for calcite, dolomite and gypsum are approximately 2.13, 0.98 and -4.19, respectively. This indicates that there is a potential risk of scaling due to calcite.

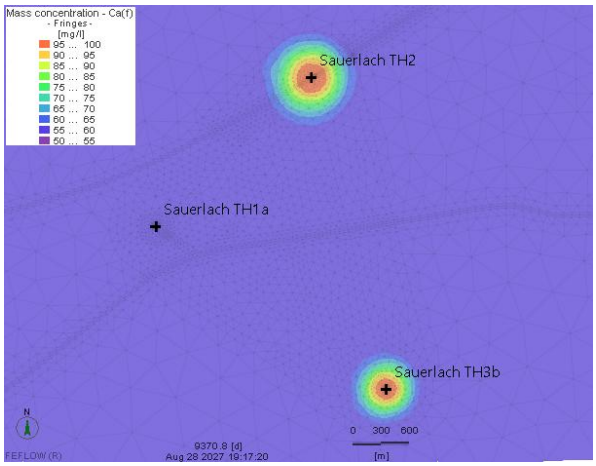


Figure 9. Simulated Calcium (Ca) concentration (mg/L) near the proximity of the geothermal system after 14 years.

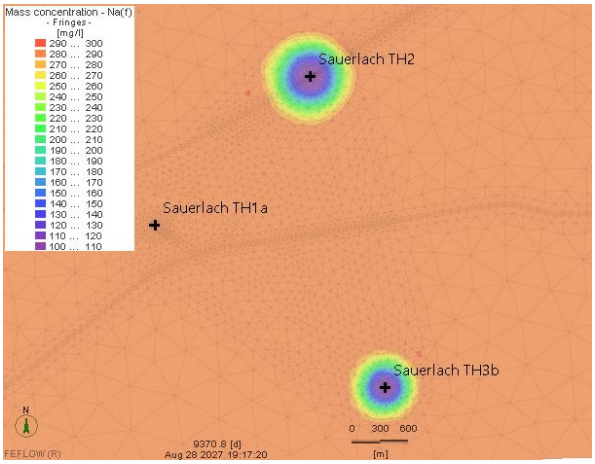


Figure 10. Simulated Sodium (Na) concentration (mg/L) near the proximity of the geothermal system after 14 years.

4 CONCLUSIONS

A FEFLOW 3D numerical model was developed to represent the flow, mass, chemical and heat processes in the Molasse basin. The chosen modelling area was near Sauerlach and included the geothermal triplet (conformed by the wells Th1a – Th2 – Th3b).

The geochemical modelling in PHREEQC successfully could identify the major equilibrium phases to present the measured water quality at well Th2. Subsequently, these results were used to model the reactive transport in FEFLOW by means of the module piChem. This FEFLOW add-ons enables the coupling to PHREEQC.

The preliminary indicates a potential risk of scaling due to calcite with a saturation index of 2.13. Further modelling analysis are required to verify this observation. For example, the present study assumes as a practical simplification that the entire reservoir has the same water quality. Under real conditions there are other minerals, which may play a role for the scaling.

Furthermore, the authors recommend to an in-depth numerical modelling at the well borehole scale. Such as approach has the practical advantage of speed-up numerical calculations to a much practical level.

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