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Hydrochemical Indicators for Sustainable and Optimized Geothermal Use of Deep Groundwater

Annette Dietmaier and Thomas Baumann
Chair of Hydrogeology, Technical University of Munich, Munich, Germany

Geothermal heat and power generation are two of several competing uses of deep groundwater reservoirs. The stress state of these slowly regenerating systems is increasing as drinking water production from shallow resources suffers from anthropogenic influences: overexploitation, total depletion, and deterioration through anthropogenic contaminants are exacerbated by a climate change-induced failure to recharge. In contrast to shallow groundwater, deep aquifers are shielded from short-term influences, like contamination, by protective overlying strata. The groundwater age is generally much higher, indicating slow regeneration processes because the system is nearly closed in its natural state. Recent data, however, suggests that this assumption is not valid for many geothermal systems with high flow rates. Therefore, a careful assessment of all competing operations using deep groundwater reservoirs is required. It should focus on the interactions between different aquifers and those within the reservoirs, all leaving their marks on the waters' hydrochemical composition.
The lack of dedicated monitoring wells around geothermal production and injection sites makes it difficult to quantify the development of these reservoirs' flow patterns. Furthermore, regular complete analysis data are usually only available at long intervals of 12 months. Still, short-term flow path development is a crucial factor in assessing heat extraction efficiency. Impaired extraction due to preferential flow paths forming between production and injection sites will degrade overall operation efficiency.

Here, we challenge state-of-the-art practices for monitoring deep aquifers. Based on decades worth of hydrochemical data on groundwater extraction at both single-well operations and geothermal doublets, we discuss how hydrochemical signatures can help determine the grade of sustainability at which deep geothermal wells are operated. Acknowledging that these assessments depend on an adequate database, and that deep groundwater research is plagued by notorious data scarcity, we tested the application of virtual sensors to these wells was tested. Lab experiments complete the analysis, quantifying the kinetics of the fluid-matrix interactions between the injector and producer.

The outcomes of this dissertation include a statistically reproducible algorithm assessing how sustainably a well is operated, focusing on the inherent dynamics at play in deep groundwater. A series of regression analyses conclude that the databases associated with deep groundwater wells are still insufficient to train virtual sensors; however, they allow conclusions on the required minimum amount of hydrochemical analyses needed to adequately represent inter-seasonal fluctuations in the aquifer. Fluid-matrix interactions result in threshold values for hydrochemical changes, which serve as a trigger to review well operation strategies and to update hydraulic and thermal models. They also indicate that changes are likely following an increasing dynamic because the surface area available for reactions increases geometrically and in roughness. Our calibrated model shows that decreasing the injection temperatures and adding CO_2 as a scaling inhibitor significantly increases the reservoir's reactivity.

Hydrochemical data can provide valuable insight into the flow processes in deep reservoirs, which are inaccessible otherwise. With smart sampling procedures and a tailored set of parameters, acquiring relevant data becomes feasible with relatively small financial investments.