# Hydrological Characterization and Optimization of In-Situ Recovery

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## Abstract

The performance of in-situ recovery (ISR) of technology metals is mainly determined by the appropriate control of both hydrological (flow) regimes and geochemistry (Märten 2015). This paper focuses on the hydrological optimization of ISR with regard to wellfield design for maximizing recovery in an economic context on the one side and minimizing environmental impacts as an important precondition for regulatory procedures on the other side.

Hydrological modeling for ISR performance is presented for both real site and hypothetical conditions in three respects: (i) optimization of wellfield design in local scale for maximum recovery in dependence on ore morphology and hydrogeological conditions, (ii) control of mining fluid inside the wellfields and minimization of its migration in ongoing ISR operations, and (iii) evaluation of post-mining aquifer restauration in terms of natural attenuation and active measures in a regional scale.

In this context, challenging and limiting factors for ISR hydrology are addressed with regard to confinement condition, porosity/permeability, aquifer pressure conditions, and saturation (also considering ISR within the vadose zone). It is demonstrated that ISR simulations in this general scope require the application of 3D hydrological modeling, in particular in the case of irregular and massive deposit morphologies and/or heterogeneous hydrological conditions. The simulations were conducted with the finite element software FEFLOW (Diersch 2014).

Key words: In-situ recovery (ISR), wellfield design, 3D hydrological modeling, aquifer restoration

## Introduction

ISR is applied to extract metals from (typically sedimentary) subsurface ore bodies by injecting a chemical leaching solution (leachant) into the ore zone to mobilize the metal(s) of interest and pumping the pregnant leach solution (PLS) to the surface for further processing. ISR is an alternative to conventional mining technology (underground and open-pit mining). It has many advantages including less environmental impact (no destructive changes to the landscape, no waste rock piles, and no tailings), less labor requirements and reduced total costs, provided that the hydrogeology and mineralogy/geochemistry of the ore deposit enable its application.

The development and testing of ISR for uranium mining has started in the early 1960s in the former USSR and USA. Later ISR of uranium has been successfully applied in Australia, Kazakhstan, Uzbekistan, Ukraine, Czechoslovakia, former Eastern Germany and China (Taylor 2004). Attempts to use ISR for other metals like copper and gold are ongoing, e.g. there are several copper ISR prospects in the USA like the Gunnison Project (Excelsior Mining), Van Dyke Project (Copper Fox Metals) and Florence Project (Taseko Mines). Martens (2012) and Wang (2013) investigated gold mining using ISR. Currently, several international research programs focus on the development/application of ISR technology (including aspects of bioleaching) to (critical) technology metals, e.g. EU-funded BioMOre project, German r$^4$-SEM$^2$ project (recovery of rare earth elements REE from ion-adsorption clays), the British SOS RARE project and others, cf. relevant websites.

The applicability (and risks) of ISR has to be examined for each deposit individually in dependence on host-rock characteristics, orebody specifics and other site conditions. Hydrological modeling is a valuable tool to investigate ISR fluid-flow regimes in regional (aquifer) and local (ISR wellfield)

scale. The outcome from hydrological modeling of ISR is typically used to setup reactive transport simulations to optimize ISR geochemistry. A consistent combination of 3D hydrological modeling of ISR wellfield performance with reactive transport approaches is a promising but highly complex and challenging task. Nicolai et al. (2016) consider essential aspects of geochemical reactive transport modeling of ISR in more detail. The present study focuses on the hydrological characterization of ISR.

In general, ISR is being applied to sedimentary hosted deposits that meet well-defined conditions for ISR amenability including (i) confined aquifer hosting the deposit with no critical hydrologic connectivity to adjacent formations (e.g. due to tectonic faults), (ii) effective (free-fluid) ore porosity and corresponding permeability, and (iii) appropriate mineralogy/geochemistry enabling the effective leaching of metals of interest with regard to both thermodynamic conditions and kinetic rates (Märten 2015). In addition to typical ISR applications, the present paper addresses conceivable options to use ISR in alternative cases, high-lighting the limits and possibilities of modifications from the perspective of 3D hydrological modeling:

(i) Application conditions and constraints of ISR with regard to deposit morphology and hydrogeology (emphasizing heterogeneity, porosity/permeability limits and conditions to improve permeability by fracturing),

(ii) Specific options for optimizing the wellfield design in order to maximize the contact of mining solution with the orebody at sufficiently high pore volume exchange rates,

(iii) Embedding the (local) wellfield simulation in a regional scale model to examine potential environmental impacts, investigate different post-mining scenarios for aquifer restoration as well as to evaluate long-term effects, e.g. natural attenuation.

## Application Conditions and Limits of ISR

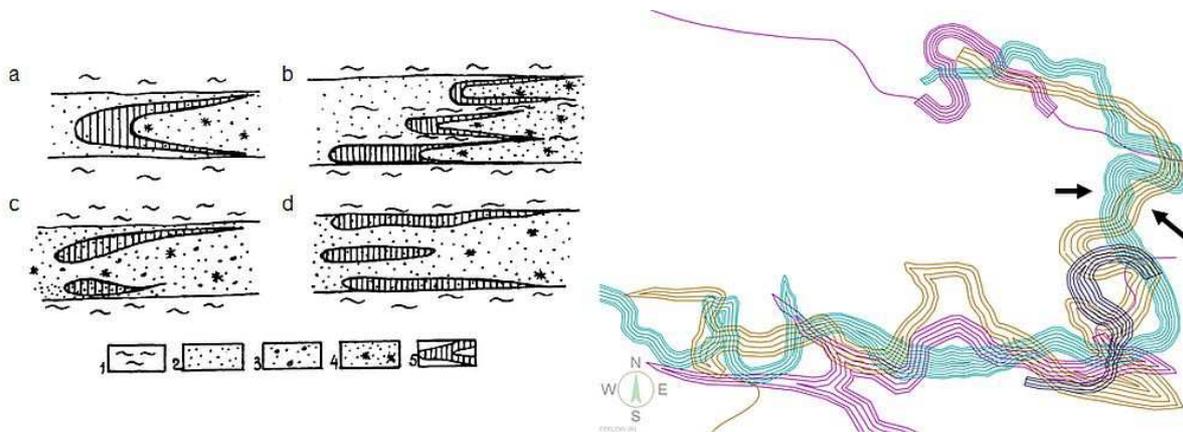*Hydrogeological Conditions.* A detailed understanding of hydrogeological conditions in and around the formation hosting the deposit is required to investigate the efficiency of ISR operation and to estimate potential environmental impacts. The porosity and permeability (hydraulic conductivity) of the mineralized formation is one of the decisive factors for ISR feasibility, determining the leachant contact with the ore, leaching rates and recoveries. The (free-fluid) porosity determines the total volume of leachant in the ore formation (effective pore volume $V_p$) and the residence time inside the orebody at given flow rate Q, expressed in terms of the pore volume exchange rate $q = Q/V_p$ (typical values in the order of $10^{-1}$ $d^{-1}$). Efficient ISR performance can be achieved for hydraulic conductivities exceeding 1 m/d, but ISR could also be operated at somewhat lower values (IAEA 2001) depending on other conditions (mentioned below) and wellfield design. The higher (and more uniform) porosity/permeability, the better is the contact between leachant and ore, the higher is ISR efficiency.

Preferably, the aquifer of interest meets confinement conditions, i.e. it is enclosed by impermeable layers (aquitards) to assure that there is no hydraulic connectivity to adjacent aquifers or surface waters. In addition to appropriate stratigraphic conditions, there should be no (tectonic) faults or fractures causing unintentional spreading of leaching solution. Further hydrogeological conditions for efficient ISR performance include (IAEA 2001):

- Sufficient hydraulic head above the extractor screens (in the order of $10^1$-$10^2$ m);

- Adequate thickness (up to 10 m) of the mineralized zone (too low thickness impedes targeting, too high thickness requires staged screening of wells);

- Moderate depth of deposit from surface (costs for drilling and well construction);

- No or minor interference by impermeable intersections (e.g. shale, clayey layers, cemented sediments) that could disturb hydraulic connection between injection and production wells.

*Deposit Morphology.* The morphology of (typically sedimentary) orebodies amenable to ISR can be highly variable. It results from geological-mineralogical, hydrogeological and geochemical conditions (IAEA 2001). Sedimentary uranium deposits are classified in the following categories: (i) rollfronts, e.g. distributed at continental basins, mixed fluvial-marine genesis, or multi-episodic distal rolls (fig. 1 a-b), (ii) stratiform or tabular (lenticular) shape (fig. 1 c-d), (iii) basal channels e.g. distinctive paleodrainage or complexly braided fluvial systems, and (iv) tectono-lithologic e.g. redistributed

primary uranium, e.g. hosted close to a fault (Dahlkamp 2009). ISR is applicable mainly to categories (i) to (iii). Usually, rollfront-like deposits have the highest concentrations of minerals within the central, most massive part that can reach a thickness from a few meters up to a few tens of meters (IAEA 2001).



*Figure 1 (Left) Morphology of roll-type deposits: a) simple roll-type deposit, b) series of simple rolls within aquifer with zones of reduced permeability, c) stratiform deposits with no roll, d) lenticular deposits at several levels: 1 - clay, 2 - sand, 3 - gravel, 4 - limonitizations, 5 - ore deposit (modified after IAEA 2001), (Right) Map of multilevel rollfronts in aquifers with different groundwater flow directions.*

## Optimization of Wellfield Design

Hydrological modeling is usually applied for (i) wellfield design (injection, extraction and monitoring wells), and (ii) specification of operational parameters. Wellfield design comprises the geometry of injection and extraction wells, including depth intervals of screened sections, in accordance to the hydrogeological conditions and outline of the orebody. In order to appropriately design ISR wellfields the comprehensive knowledge of stratigraphy, comprising the mining zone and relevant adjacent layers, as well as any irregularities (e.g. tectonic faults and impermeable beds) and heterogeneities is essential. Stratigraphic irregularities are a major concern with regard to environmental impacts and subject to scrutiny by regulatory organizations (Märten 2015).
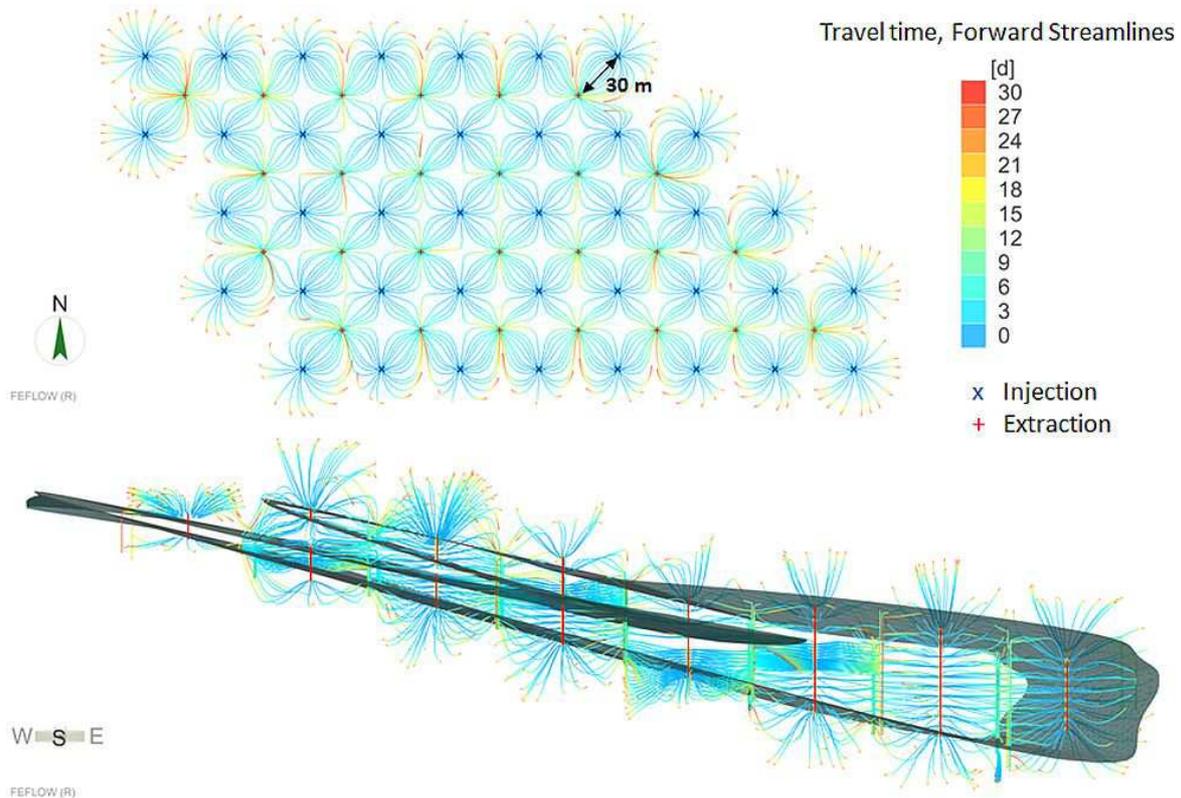
Most common wellfield designs are 5- and 7-spot patterns of injection/extraction wells, alternate well lines and free setups adjusted to irregular orebodies. Design criteria include optimum contact (pore volume exchange) of leachant and ore (in 3D), minimized migration of leachant, minimum dilution (groundwater) and uniformity of leachant flow (IAEA 2001). Arrangements of 5- and 7-spot patterns are characterized by a central extraction well surrounded by 4 or 6 injection wells, respectively. Depending on hydrogeology and ore characteristics spacing between wells range from 15 to 50 m typically.

Operational parameters include injection pressures, injection and extraction flow rates, and pore volume exchange rate (q). The achievable flow rate in a wellfield pattern is mainly determined by permeability, hydraulic head of mining aquifer above extraction screens, relevant aquifer interval and injector-extractor spacing. Typical extraction flow rates range from a few $10^0$ to $10^1$ L/s. The injection/extraction flow regime is carefully balanced to avoid/minimize the excursion of mining fluid. Typically a bleed from the leachant cycle in the order of 0.5 to 2 % is applied for better flow balance.

Fig. 2 demonstrates the wellfield optimization for a rollfront ore deposit, performed by the use of a 3D hydrological model with FEFLOW. A typical 5-spot well pattern is set up with a well spacing of 30 m between injectors and extractors. As shown in the 3D image (fig. 2, below), screening sections of the wells are positioned according to the morphology of the rollfront, resulting in longer screens within the rollfront nose and intervals of shorter screens within the limbs. Further, fig. 2 represents the travel times of fluid flow (streamlines) from injection towards extraction wells for a time period of 30 days showing the pathways lengths for the defined well design and specified flow rates. The optimization of ISR is based on the variation of flow rates, well spacing, and filter lengths in an iterative process.

The exact vertical placement of well-screens is critical for realizing a uniform leachant flow through the entire ore body (within the pattern) and, hence, a precondition for maximizing ISR efficiency.
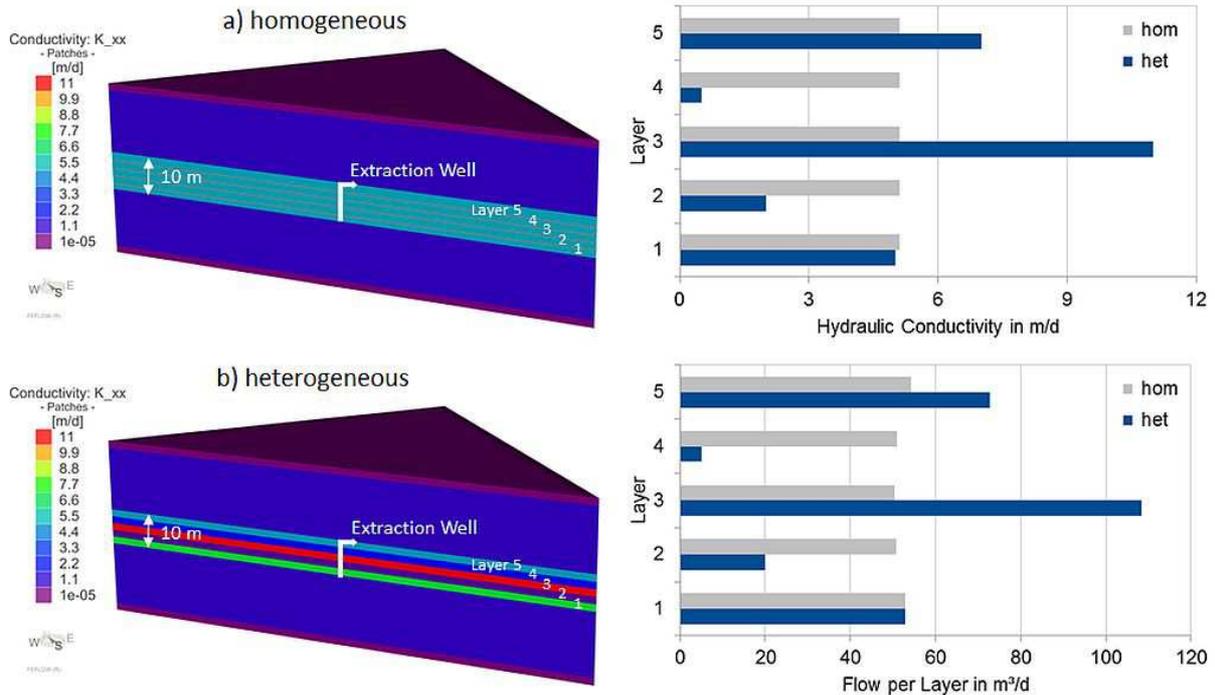
The hydrological modeling of ISR wellfields enables the evaluation of potential "dead" zones where leachant solution either bypasses or PLS accumulates along the peripheral (slower) flowpaths. Such zones could be predicted and (temporary) alternative flow regimes investigated by applying reversed scenarios where injection wells are converted to extraction wells and vice versa (role reversals).



*Figure 2 Optimization of wellfield design for a mineralized rollfront; lixiviant streamlines within a 5-spot well pattern as top view (upper image) and 3D view within the rollfront (lower image). Streamline color is indicative of travelling time (cf. legend).*

**Deposit Heterogeneities with Regard to Hydraulic Permeability and Ore Morphology**

Massive rollfronts ('noses') with a thickness in excess of 10 m are a challenge for ISR operation with regard to setting up optimized (effective) filter screen lengths and positions. Too long filter screens may not provide uniform flow of leachant caused by the natural heterogeneity within the mineral deposit. Ore layers with higher permeability are likely to be leached more preferably, resulting in a poor recovery from less permeable ore layers accordingly. This scenario is illustrated by a comparison of two numerical simulations that model the pumping from a single well in a 3D model domain (fig. 3). In both simulations the extraction well is defined by the same total flow rate (~6 L/s) and a well screen of 10 m length that is positioned in the center of a mineralized, confined aquifer. The two simulations differ regarding the specification of hydraulic conductivity K (permeability) of the mineralized ore zone that is divided into 5 sublayers. Simulation (a) considers a homogeneous conductivity along the screen length, while in simulation (b) hydraulic conductivity differs from layer to layer (fig. 3, top right), thus, defining a vertical distribution of K.
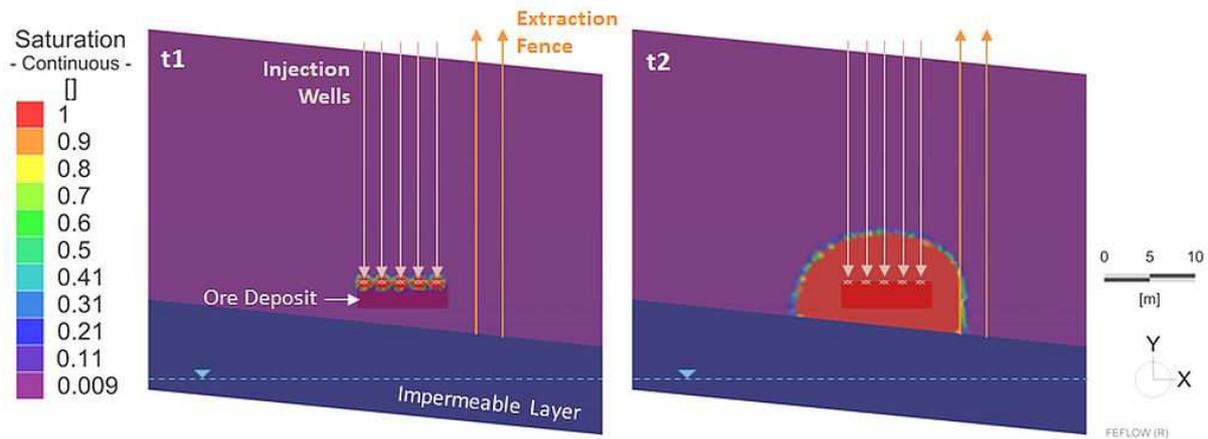
***Figure 3*** *(Left) 3D model design of a single extraction well (10 m screen) embedded within a (a) homogeneous and (b) heterogeneous aquifer hydraulic conductivity. (Right) Hydraulic conductivity (m/d) and flow rates (m³/d) per layer along filter screen for homogeneous (hom) and heterogeneous (het) model.*

Fig. 3 (bottom right) represents the resulting flow rates in the 5 layers along the filter screen. As expected, the vertical flow rate profile reflects the variation of K in the heterogeneous model. In the present example, the metal from the less permeable layers 2 and 4 would be recovered at a very low rate. Under real world conditions, the screening of ISR wells can be adjusted in accordance to the vertical permeability profile measured by using advanced borehole logging techniques (Märten 2015) to optimize recovery. In particular, effective leaching along massive ore zones can be achieved by changing screening intervals (so-called 'rescreening') consecutively during the lifetime of the wellfield. The same would apply to staggered ore formations (roll fronts) shown in fig. 1 b (left image). Rollfronts could form quite variable morphologies in superposed layers as a consequence of different groundwater flow regimes during the deposition of such sedimentary ore bodies (see fig. 1, right image). Here the challenge is to set-up a wellfield design that could be applied in different depths consecutively by the readjustment of flow regimes (e.g. role reversals/modifications) in general and filter screens of individual wells in particular. Thus, drilling and well construction costs could be minimized. In summary, provided the mineralized ore zones are well mapped, 3D hydrological modeling is a powerful tool to optimize the design of ISR wellfields to realize an efficient/economic recovery and, by the same token, to minimize the probability of leachant excursions.

### Modified/Adjusted ISR Applications

***ISR Application in Vadose Ore Zones.*** If the ISR amenability criteria are not met entirely, modifications or adjustments of the classical ISR operation by wellfields are conceivable, subject to feasibility and efficiency. Such non-ideal application cases include (i) unconfined deposits with low to moderate hydraulic heads, (ii) deposits hosted in the vadose (unsaturated) zone, or (iii) deposits characterized by low porosity and permeability. Modeling ISR under such (originally) unfavorable hydrogeological conditions is a valuable tool to investigate new technological approaches. In the case of unconfined conditions along with low hydraulic heads, hydrological modeling is suitable to estimate appropriate well configurations and flow regimes, in particular to prevent pumps from running dry. Hydrological conditions are quite different for ISR applied to an ore zone within the (unsaturated) vadose zone. A possible leaching approach is gravity-driven, percolate leaching regime combined with the extraction of the PLS via drainage systems (ADEQ 2004). Depending on the specific site conditions, the ore zone could be located above, below or partly below the water table. A

water table above the level of extraction would induce a higher dilution of PLS (impacting metal recovery). Modified ISR regimes are conceivable if the ore body is located in a formation with a natural gradient and an impermeable underlying layer to prevent leachant migration. An exemplarily simulation performed by the use of FEFLOW (Diersch 2014) is demonstrated in fig. 4. The injection and extraction wells are set up for an ore body located in the vadose zone. The original groundwater table is below the ore zone within the underlying impermeable layer. The simulation shows the gradual saturation of the ore zone and the surrounding area at two different time steps t1, shortly after startup, and t2, when the PLS is reaching the extraction site. The model allows the variation of injection/extraction rates and pressures to achieve hydrologic control of leachant flow to meet ISR objectives and environmental requirements.



***Figure 4*** *ISR application within the vadose zone; gravity-driven saturation of the ore deposit and adjacent area for two different time steps t1 (shortly after startup) and t2 (reaching extraction).*

***Fracturing of Less Permeable Ore Formations.*** In order to overcome the technical challenges of low porosity and permeability, fracturing by different means (hydraulic, chemical, thermal, high-voltage, blasting, etc.) has been considered to achieve the leachant-ore contact required for an economic recovery (Robinson 2016). Fracturing and fracture modeling approaches are known from the oil and gas industry, like discrete fracture network (DFN) modeling (Dershowitz 2011). Its transferability to ISR operations needs to be evaluated with regard to the different flow characteristics of oil/gas and leachant. Another challenge in fracture modeling is the proper replication of the fractures within the model due to their difficult visualization that is subject of ongoing testing. Whereas high-permeable sedimentary ore formations, e.g. hosted in sandstone, are characterized by a rather uniform free-fluid porosity enabling an ideal contact of the leachant with the metal-bearing minerals, the flow through fractured ore formations is preferential. In the latter case, the kinetics of leaching is by far more controlled by diffusion, thus, retarding recovery. An economic recovery is only conceivable for very high ore grades of very valuable metals.
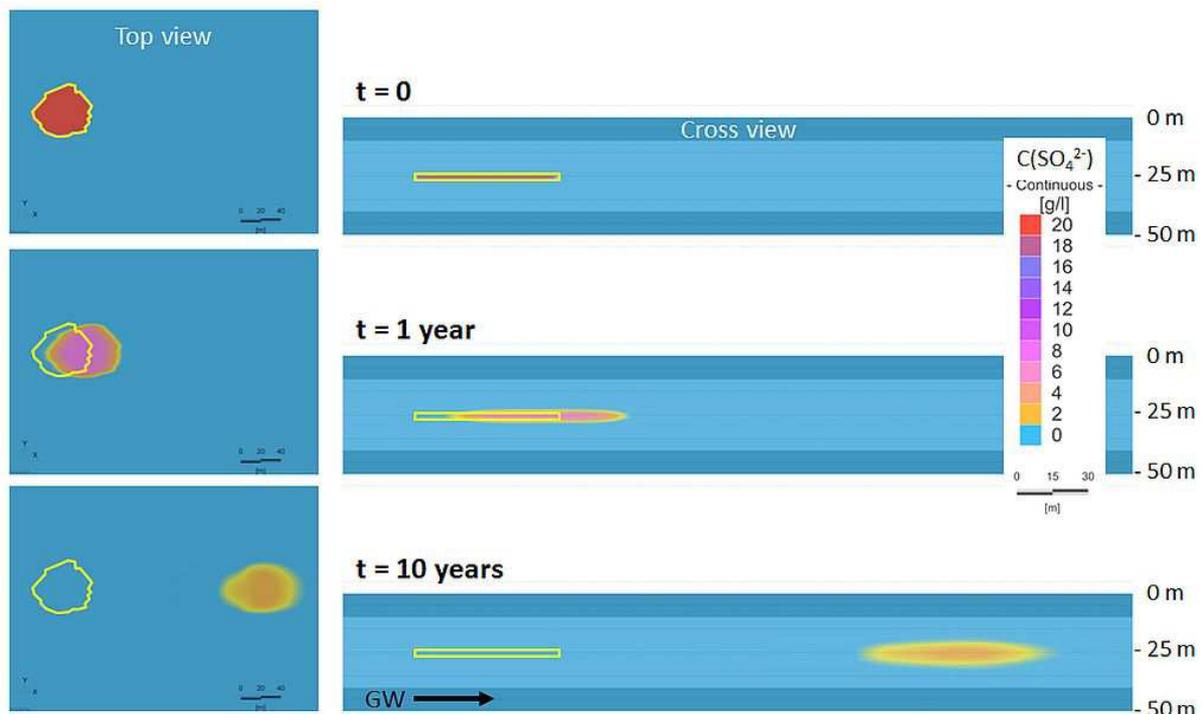
## Regional Scale Model

So far, we considered the advantages of hydrological modeling in a local (ISR wellfield) scale in terms of maximization of metal recovery. In regional scale, hydrological modeling is used to investigate environmental impacts of ISR in general, monitoring in the vicinity of operating ISR wellfields, post-mining monitoring and restoration strategies as well as relevant long-term effects such as natural attenuation (NA). For these applications, the wellfield hydrology is embedded into the regional groundwater model to simulate the effect of temporary ISR operation in a wider scale. Potential environmental impacts during ISR operations include (i) the migration of mining solution along the natural groundwater flow within the mining aquifer, (ii) unintended excursions caused by (tectonic) faults, discontinuous sealing layers (aquitards) and other exceptional hydraulic connectivity in both horizontal and vertical direction. Potential impacts and risks can be addressed within a regional-scale hydrological model. In particular, such simulations support the design of a representative monitoring systems (observation wells) during and after ISR operations.

The setup of the regional-scale hydrological model with embedded wellfields requires the following data input and procedures (calibrations) to be followed for reliable simulations:

- The appropriate representation of the regional geological stratigraphy is fundamental. Additionally, possible hydraulic connectivity between strata and along tectonic faults or thinning of confining layers should be considered. Input data can be derived from geophysical surveys (in particular, seismic) and borehole data (logging data, core assays).

- The permeability and porosity of all relevant formations (strata) including the mineralized ore zone are deduced from (i) geophysical borehole logging, (ii) laboratory assays of available core samples, (iii) aquifer pumping tests. Whereas the first data categories refer to smaller scale conditions, pump tests provide wider-scale information for aquifers and other strata.

- The initial hydraulic head data (potentiometric surfaces) is used for the calibration of the hydrological model and for simulating natural groundwater flow (baseline conditions).

- The anisotropy of permeability (lateral versus vertical) is quite significant for sedimentary formations. It can be determined by testing core samples.

- All relevant boundary conditions need to be considered appropriately, in particular sink and source terms that contribute to the groundwater flow regime like recharge/discharge, precipitation/evaporation, pumping/injection, surface water boundaries.

Post-mining conditions inside former ISR mining aquifers were studied by simulating the propagation of a mining solution body in 3D. For this purpose, the 3D hydrological model was first generalized for mass transport calculations incorporating a non-reactive species. Most important transport parameters including porosity and dispersivity had to be adapted. Representative results of such a 3D mass transport simulation are shown in fig. 5. The fate of mining fluid is indicated by time-dependent $SO_4^{2-}$ concentration profiles considering horizontal and vertical cross-sections. Essentially, the mining fluid moves along the natural groundwater flow, spreading in 3D according to permeability and dispersivity conditions.



**Figure 5** *Fate of tracer solution ($SO_4^{2-}$ in g/L) from an abandoned mine site in horizontal (top view) and vertical (cross view) direction caused by groundwater (GW) induced dilution (non-reactive species transport).*

FEFLOW offers two possible approaches to incorporate *reactive* transport in 3D. First, geochemical reactions can be incorporated by user-defined reaction rate specifications, which require a comprehensive understanding of the main geochemical reactions and species derived from more sophisticated 1D reactive transport models (Nicolai 2016). Second, the piChem plug-in could be applied that allows for coupling FEFLOW with PHREEQC (Parkhurst 1999). These two approaches to 3D reactive transport modeling were studied for a homogeneous 5-spot ISR wellfield by Nicolai et al. (2015) showing that both approaches produce reasonable results, however, extensive computation times and numerical constraints restrict the applicability of the piChem approach for ISR optimization.

## Conclusions

3D hydrological modeling is a state-of-the-art approach to support ISR projects with regard to feasibility studies, regulatory procedures, ISR wellfield design, optimization of ISR performance, monitoring/control of aquifer conditions during and after (post-mining) ISR, and aquifer restoration. Based on incorporating the comprehensive input from 3D structural models of the ISR district, the consistent embedment of (local) wellfields into a regional-scale hydrological model has been demonstrated for setting up and optimizing ISR operation as well as studying environmental impacts by applying the software FEFLOW (Diersch 2014). It is also suitable to investigate the 3D mass transport of main chemical species considering the kinetics of determining mineral-solute interactions.

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