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# Lithium Co-Production from Hydrothermal Reservoir, Eastern Upper-Rhine Rift Valley: Solute Output Prediction Based on Mid-Late Signals from Inter-Well Tracer Test

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**ABSTRACT**

Recently, we derived a tracer-based method to forecast the depletion of a co-produced solute during fluid re-circulation in a geothermal reservoir operated by means of a well doublet. This method of Behrens et al. (2022) was deemed model-independent, viz. the measured signals of any conservative artificial tracer from inter-well or inter-horizon circulation tests, conducted under representative flow conditions, can be used to predict the co-production output of any fluid-mined solute, and its gradual depletion during fluid turnover, irrespective of the availability and parametrizing of a reservoir model (up to the effects of depletion-induced water-rock interactions, which are difficult to model in detail, but mostly negligible).

We also explained two generic (model-independent) differences between solute depletion rates in petrothermal versus hydrothermal reservoirs, with major implications for the economic efficiency of any solute mining endeavor.

Over the past twelve months, at one of the tested geothermal sites, Eastern side of the Upper Rhine rift valley, mid-to-late signals have been recorded, enabling to significantly constrain the uncertainty of lithium output predictions, and to further reduce their dependence on a particular reservoir model. Some ten more tons of lithium per reservoir fluid ToV (turnover volume) may not sound like a dramatic improvement, compared to inferences made (Ghergut et al. 2023) from the incipient 'nil signal' information in conjunction with a largely 'closed-boundary' reservoir model. The noteworthy aspect, though, is that lithium mid-term depletion can now be re-assessed more robustly, i.e. with a single-parameter focused sensitivity w. r. to reservoir hydrogeology and hydraulics, provided that the forced-gradient inter-well flow field, as established so far, is going to be maintained in the long run.

On the other hand, at this stage, the available tracer signal yet cannot 'anticipate' how its large-time asymptotic recovery ratio might increase or decrease if the inter-well flow regime would vary significantly. Augmenting the forced-gradient flow rate by some (desired, and cautiously deemed as hydraulically 'feasible') 40%–50% would accelerate lithium co-production (proportionally to the flow rate), which, economically, is a sensible thing to do, of course, though it might not significantly augment the total (cumulative) output.

## 1. INTRODUCTION

In past years' contributions, we derived a tracer-based method to forecast the depletion of a co-produced solute (like lithium) during fluid re-circulation in a geothermal reservoir operated by means of a well doublet, and illustrated its use for various reservoir settings in the Upper Rhine rift valley and the N-German sedimentary basin. The method of Behrens et al. (2022) was deemed model-independent, viz. the measured signals of any conservative artificial tracer from inter-well or inter-horizon circulation tests, conducted under representative flow conditions, can be used to predict the co-production output of any fluid-mined solute (in particular: lithium), and its gradual depletion during fluid turnover, irrespective of the availability and parametrizing of a reservoir model (distributed- or lumped-parameter, numerical or analytical), as long as the fluid-mined solute behaves itself conservatively, similarly to the added tracer. The tracer-based approach to lithium co-production forecast is outlined in fig. 1, with details to be found in past publications (Behrens et al. 2022, Ghergut et al. 2023), where we also explained two generic (model-independent) differences between solute depletion rates in petrothermal versus hydrothermal reservoirs, with major implications for the economic efficiency (Goldberg et al. 2022a) of any solute mining endeavor.

So-called 'sustainability gains' by virtue of depletion-induced water-rock interactions (positive term, column in orange in fig. 1) are purely hypothetical at this stage; they are supposed to play the decisive role for lithium co-production from geothermal reservoirs in the Northern German basin, whereas for geothermal reservoirs in the Upper Rhine rift valley, while generally very difficult to quantify accurately, they can be expected to be largely negligible. In this paper, we shall thus focus on the negative term ('sustainability losses'), with the tracer-based forecast workflow outlined in the blue column of fig. 1, which is largely site-independent; all site-specific aspects being captured synthetically by the signal of a conservative artificial tracer that was added alongside inter-well circulation.

With a one-time, concentrated tracer addition ('short pulse'), the formula shown at the bottom of fig. 1 applies. If the tracer is added continuously, then the last integral of that formula becomes, so to say, already computed by the tracer, i.e., it can be replaced by its gradually cumulated recovery, which (up to signal deconvolution) is equivalent to the measured signal of the continuously added tracer.

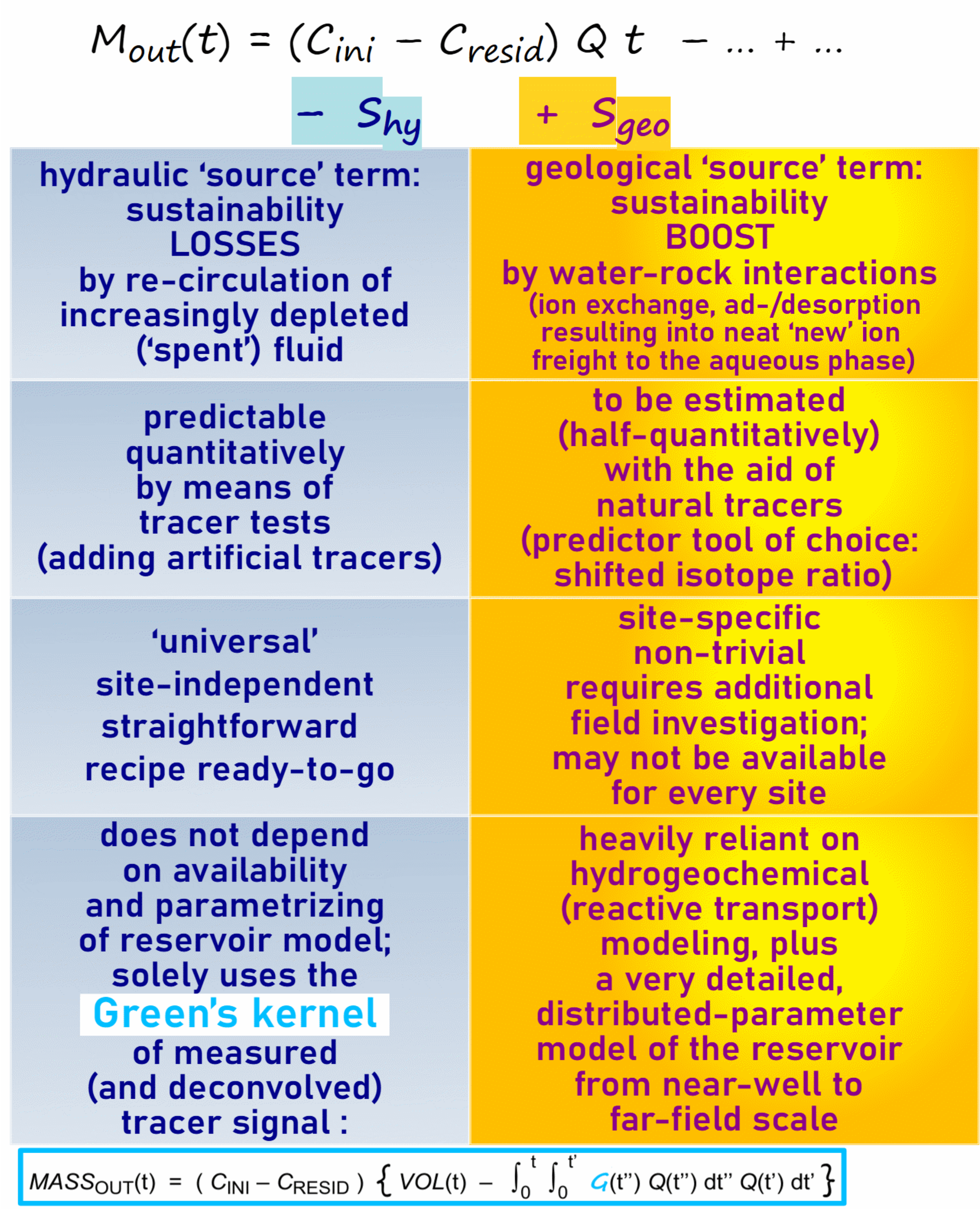


**Figure 1: Tracer-based approach to the mid- and long-term forecast of cumulative lithium output. So-called 'sustainability gains' by virtue of depletion-induced water-rock interactions are purely hypothetical at this stage; they are supposed to play the decisive role for lithium co-production from geothermal reservoirs in the N-German basin, whereas for geothermal reservoirs in the Upper Rhine area, while generally difficult to quantify accurately, they can mostly be discarded. We thus focus on the negative term ('sustainability losses'), with the forecast workflow outlined in blue.**

By contrast, at early tracer-test stages, when the sole information available is that the tracer signal stays below the detection limit (DL) until the current time, or when the incipient tracer breakthrough just becomes detectable, this 'nil signal' or 'first breakthrough' information (cf. fig. 5 of Ghergut et al. 2023) can be fed into a predictive model for solute co-production, relying on certain assumptions on reservoir structure and boundaries, the single decisive parameter of which is equivalent to the large-time asymptotic tracer recovery – which, obviously, cannot be told from 'nil signal' or 'first breakthrough' data; thus, at early tracer-test stages, solute co-production prediction remains model-dependent.

At later stages, the more tracer is gradually recovered at production wells, the less uncertain the prediction of its asymptotic recovery ratio becomes; the latter yields the missing (implicit) 'curve parameter' to the "reservoir potential" estimations ("theoretically extractable amount" scenarios) of Goldberg et al. (2022b, their fig. 5).

## 2. SCOPING SIMULATIONS OF LITHIUM DEPLETION AT MID-TERM STAGES OF FLUID RE-CIRCULATION

The approach outlined in the blue column of fig. 1, designed to be used with measured tracer signals, can also be used with simulated tracer signals, to roughly 'calibrate the expectations' at early stages of a geothermal co-production endeavor. Figures 2 to 5 show such simulations for a particular site in the Upper Rhine rift valley (Eastern side), whose geology and hydrogeochemistry characteristics were investigated, comparatively evaluated and described by Eggeling et al. (2013), Frey et al. (2022), Herzberger et al. (2009, 2010), Kölbel et al. (2020, 2021), Meixner (2009), Meixner et al. (2016), Sanjuan et al. (2020, 2022), Stober and Bucher (2015), Stober et al. (2013). Lithium co-production is currently being implemented at this site with technologies described by Kölbel et al. (2023).

Tracer concentrations in figs. 2–5 are normalized by the tracer input quantity per fluid turnover volume (ToV). Lithium depletion (shown with physical units) and cumulative output (normalized by the Li contents of one ToV) are plotted against time normalized by the re-circulated fluid's mean residence time (MRT). Reservoir heterogeneity is quantified by a synthetic, equivalent Péclet number (Pe) supposed to also reflect the effects of transport processes other than advective-dispersive (of which especially matrix diffusion is expected to play a significant role and produce long-term elevated signal tailings), as argued in Ghergut et al. (2023).

It is easily recognized that lithium depletion and cumulative output are almost insensitive to Pe in the long run (with only weak mid-term dependence on Pe), which implies that failure to accurately describe matrix diffusion processes by a single 'equivalent' Pe value is not critical, since the linear superposition of infinitely many Pe values would preserve the observed insensitivity to Pe. Thus, the single major parameter of interest (and, possibly, concern) remains the large-time asymptotic value of cumulative tracer recovery (R%).

## 3. TRACER-BASED FORECAST UPDATE

Over the past twelve months, at the above-mentioned site, mid-term signals have been recorded, deconvolved and evaluated (upper section of fig. 6), enabling to significantly constrain the uncertainty of lithium output predictions, and to further reduce their dependence on a particular reservoir model. Some ten more tons, or 15% of lithium per reservoir fluid ToV (lower section of fig. 6) may not sound like a dramatic improvement, compared to inferences made (fig. 6 of Ghergut et al. 2023) from the incipient 'nil signal' information (fig. 3 of ibid.) in conjunction with a largely closed-boundary ('insulated-reservoir') model. The noteworthy aspect, though, is that lithium mid-term depletion can now be assessed more robustly, i.e. with a single-parameter focused sensitivity w.r. to reservoir hydrogeology and hydraulics (fig. 7), provided that the forced-gradient inter-well flow field, as established so far, is going to be maintained in the long run.

On the other hand, at this stage, the available tracer signal yet cannot 'anticipate' how its large-time asymptotic recovery ratio might increase or decrease if the inter-well flow regime is going to be changed significantly (both increase and decrease scenarios being compatible with an augmented flow rate, by what is known so far about the reservoir's structural-hydrogeological characteristics, cf. fig. 7). Augmenting the forced-gradient flow rate by some (desired, and cautiously deemed as hydraulically 'feasible') 40%–50% would accelerate lithium co-production (proportionally to the flow rate), which, economically, is a sensible thing to do, of course, though it might not significantly augment the total (cumulative) output.

## 4. CONCLUDING REMARK

The co-operative research project UnLimiteD (www.geothermal-lithium.org/en), initiated by EnBW (Energie Baden-Württemberg) together with BESTEC (www.bestec-for-nature.com), KIT (Karlsruhe Institute of Technology) and the University of Göttingen, deals with lithium co-production from geothermal reservoirs in the Upper Rhine rift valley and the Northern-German Basin. The Göttingen group uses fluid tracers, natural and artificial, to estimate the overall lithium amount extractable by fluid mining in various geological settings, quantify the evolution of solute co-production rates during fluid turnover, and predict the final mass and energy output over the solute mining lifetime – which may or not exceed the thermal lifetime of a given reservoir, depending on its operation schemes; scenarios with *longer thermal lifetime* are likely to become more frequent.

Currently, the single major challenge to artificial-tracer signal evaluation and interpretation is the limited availability of flow-rate records from the geothermal plant (for varying reasons). Further non-trivial challenges might – theoretically speaking – incur from the need to foresee and quantify overall water-rock interaction effects of 'spent fluid' re-injection, the latter being depleted of its particular micro-constituent, albeit at trace levels only, while being likely acidized or 'unreliably' buffered at major-ion levels. Water-rock interactions cannot be told from conservative-tracer signals; hydrogeochemical modeling (Kühn et al. 2002, Maier et al. 2021) becomes indispensable and is likely to turn out more intricate for hybrid 'petrothermaquifers' in the Northern-German Basin (Kühn et al. 1998, Tischner et al. 2010, Feldbusch 2016) than for hydrothermal reservoirs in the Upper Rhine rift valley (Kölbel et al. 2020). For the latter, however, there is reason to assume that the positive term (as outlined in the orange column of fig. 1) will mostly remain negligible.

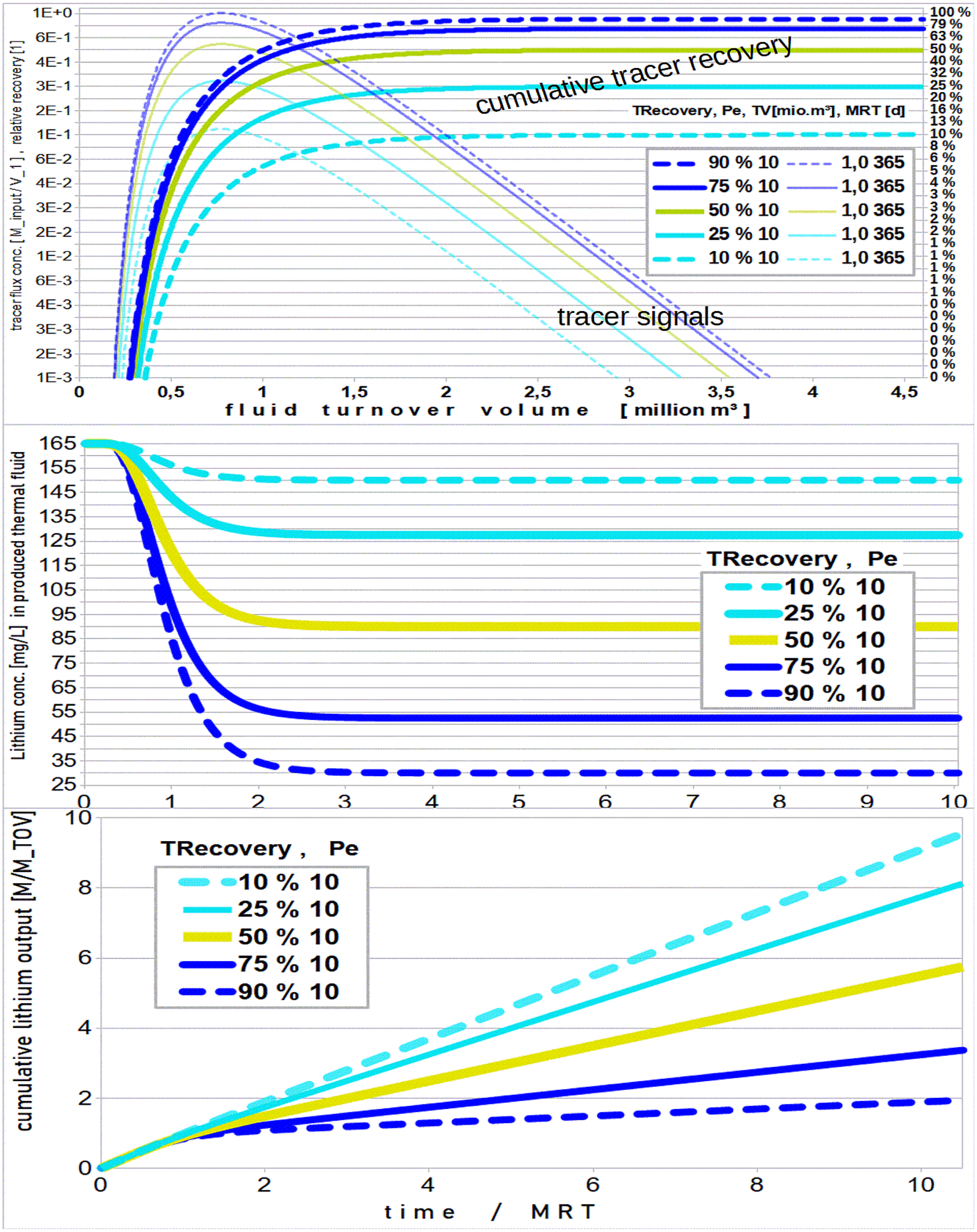


**Figure 2: Scoping simulations of tracer breakthrough signals and their cumulative recovery (normalized), plotted against physical fluid turnover (upper section), and their corresponding tracer-based forecast of lithium depletion (plotted with physical units, middle section) and cumulative output (normalized, lower section), plotted against time normalized by the fluid's mean residence time (MRT), for a relatively homogeneous reservoir (synthetic parameter Pe = 10).**

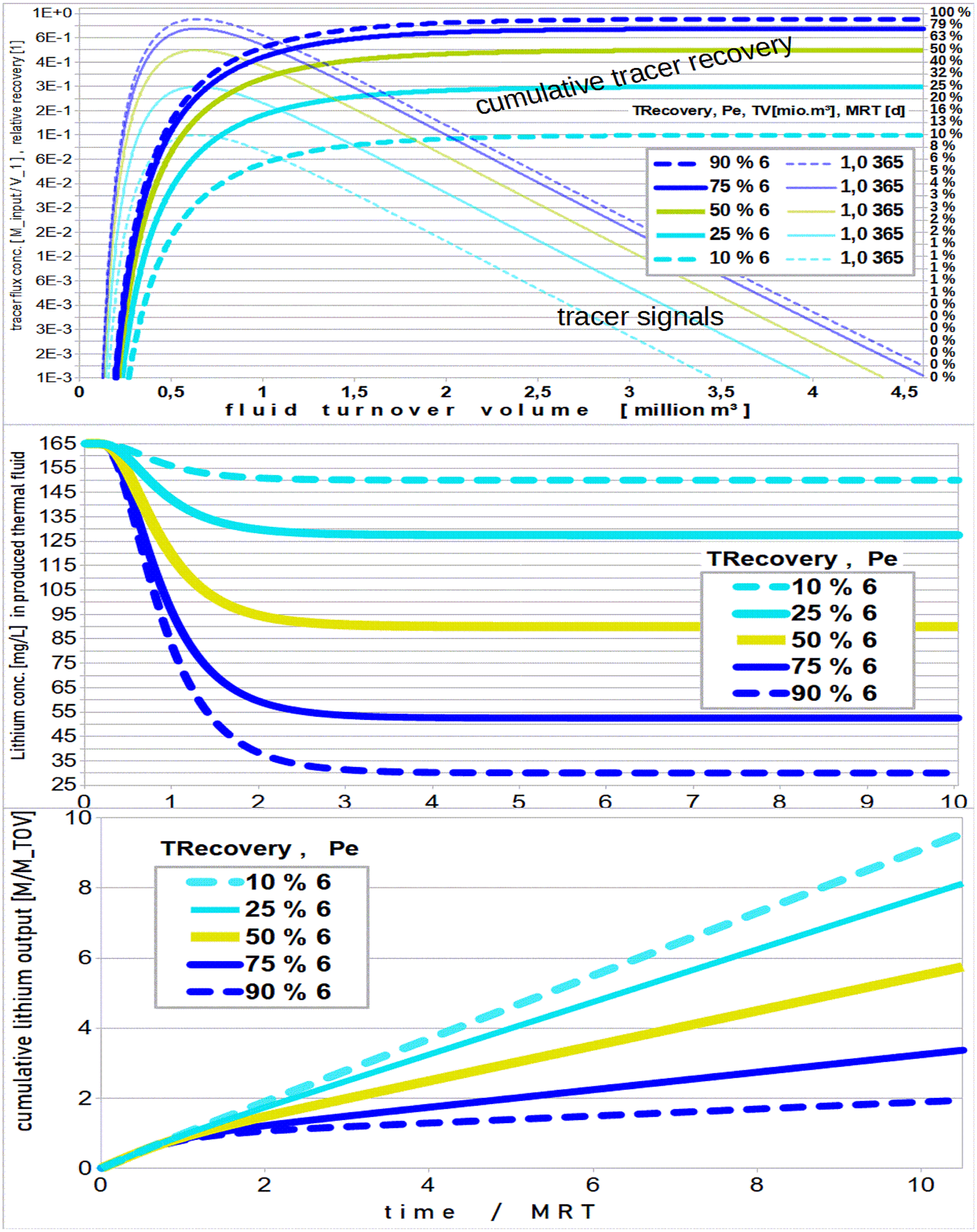


**Figure 3: Scoping simulations of tracer breakthrough signals and their cumulative recovery (normalized), plotted against physical fluid turnover (upper section), and their corresponding tracer-based forecast of lithium depletion (plotted with physical units, middle section) and cumulative output (normalized, lower section), plotted against time normalized by MRT (cf. supra), for a rather heterogeneous reservoir (Pe = 6) and/or under marked influence of matrix diffusion.**

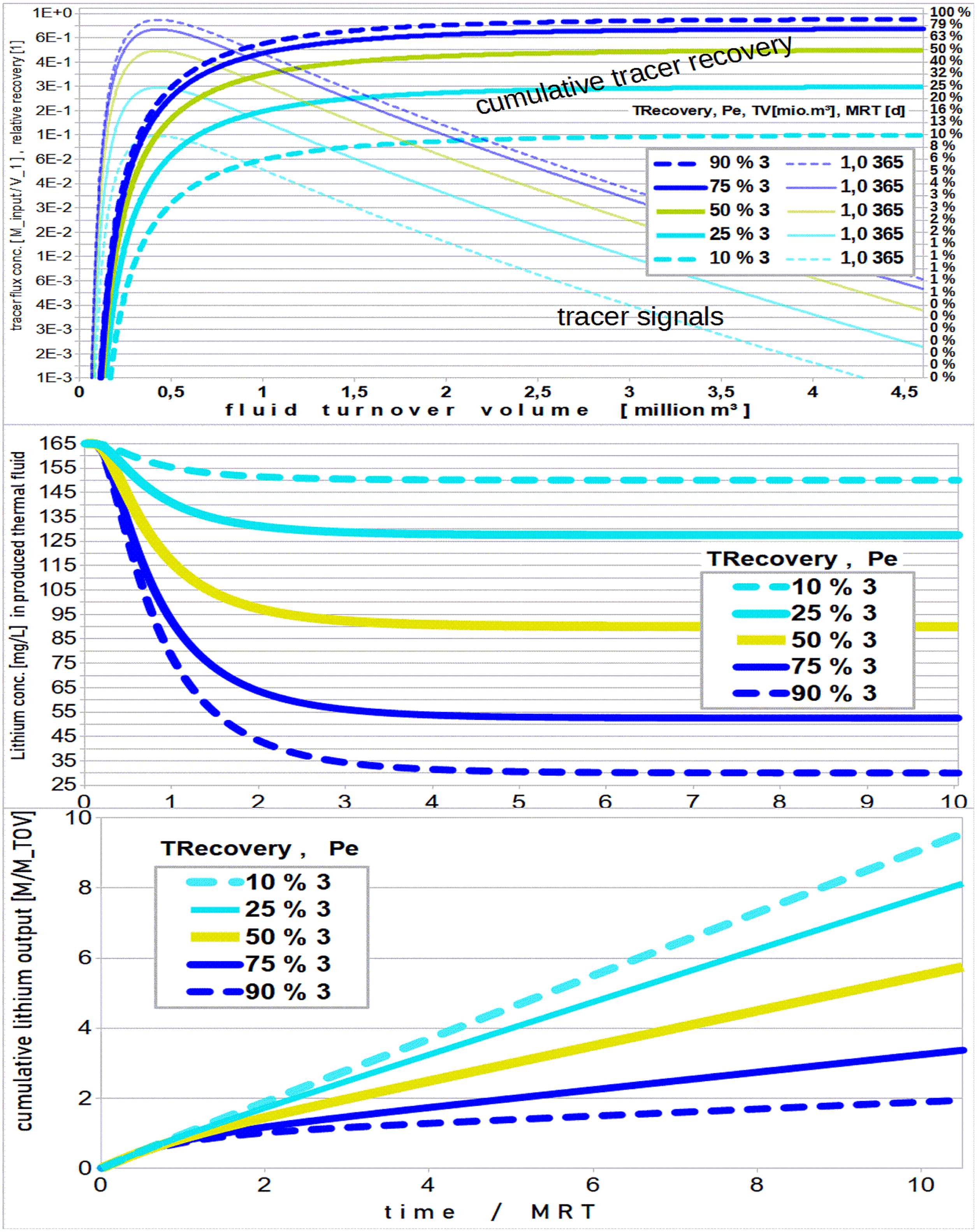


**Figure 4: Scoping simulations of tracer breakthrough signals and their cumulative recovery (normalized), plotted against physical fluid turnover (upper section), and their corresponding tracer-based forecast of lithium depletion (plotted with physical units, middle section) and cumulative output (normalized, lower section), plotted against time normalized by MRT (cf. supra), for a very heterogeneous reservoir (Pe = 3) and/or under strong influence of matrix diffusion.**

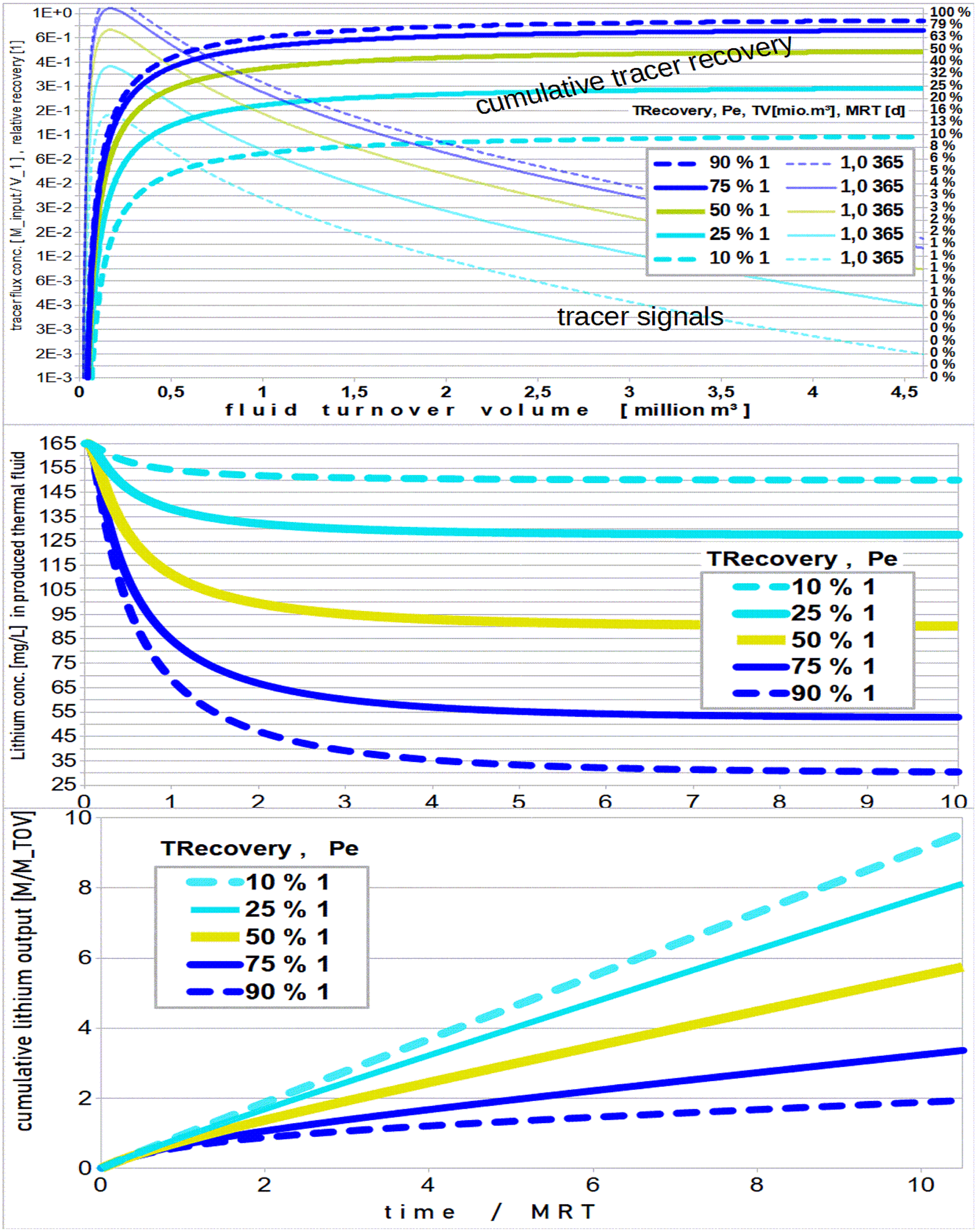


**Figure 5: Scoping simulations of tracer breakthrough signals and their cumulative recovery (normalized), plotted against physical fluid turnover (upper section), and their corresponding tracer-based forecast of lithium depletion (plotted with physical units, middle section) and cumulative output (normalized, lower section), plotted against MRT-normalized time (cf. supra), for a matrix-diffusion dominated solute transport regime (Pe = 1) and/or extremely heterogeneous systems.**

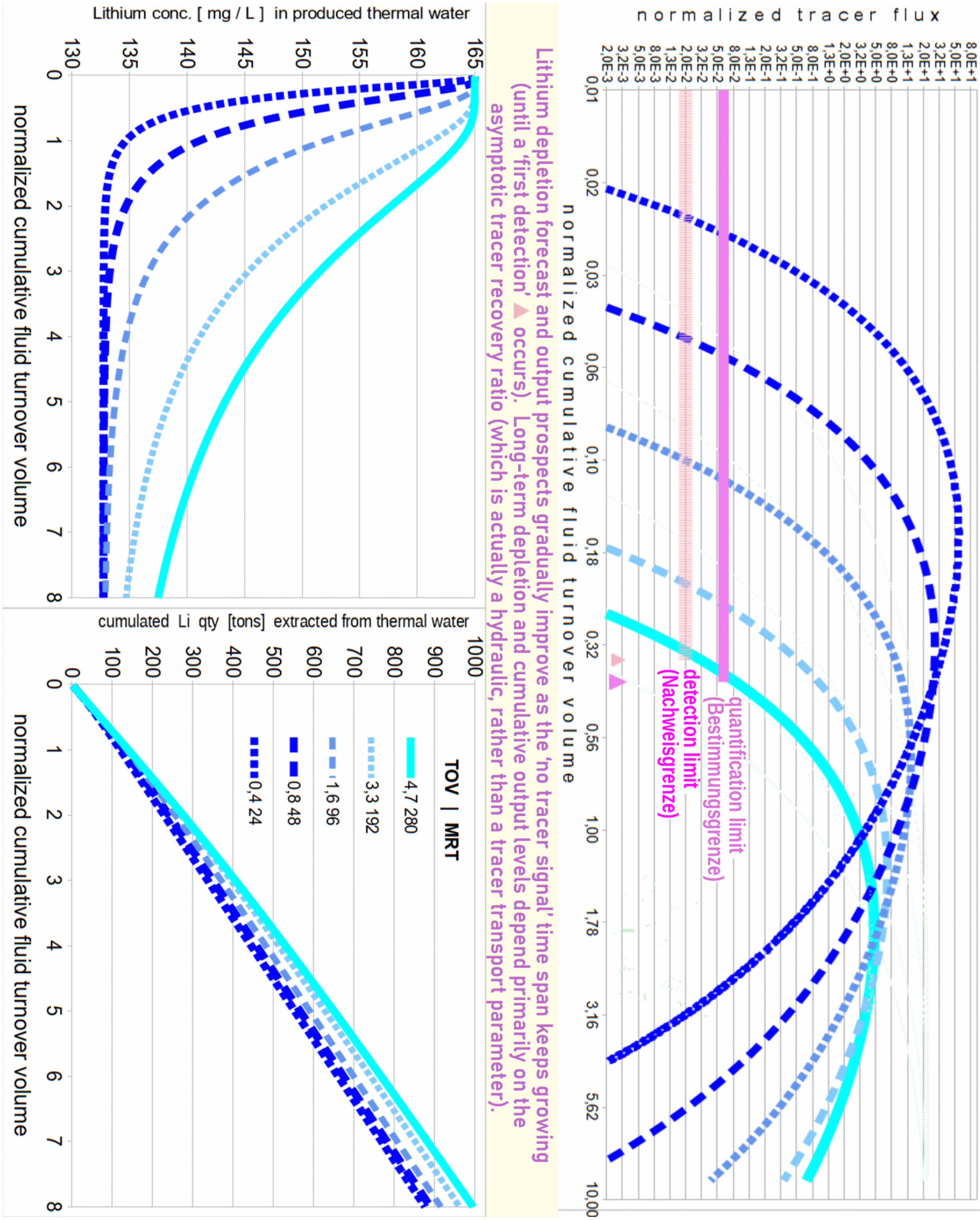


**Figure 6: As recorded to date, the conservative tracer's breakthrough signal (corresponding to the model signal in solid cyan) enables to raise the predicted cumulative output over a time span of 8 MRT by at least 15% (~from 870 to 1000 tons), compared to the early estimates (corresponding to the model signal in dashed dark blue). The actual output might even be a bit higher, since the predictions shown assume a somewhat overestimated R% value (cumulative tracer recovery).**

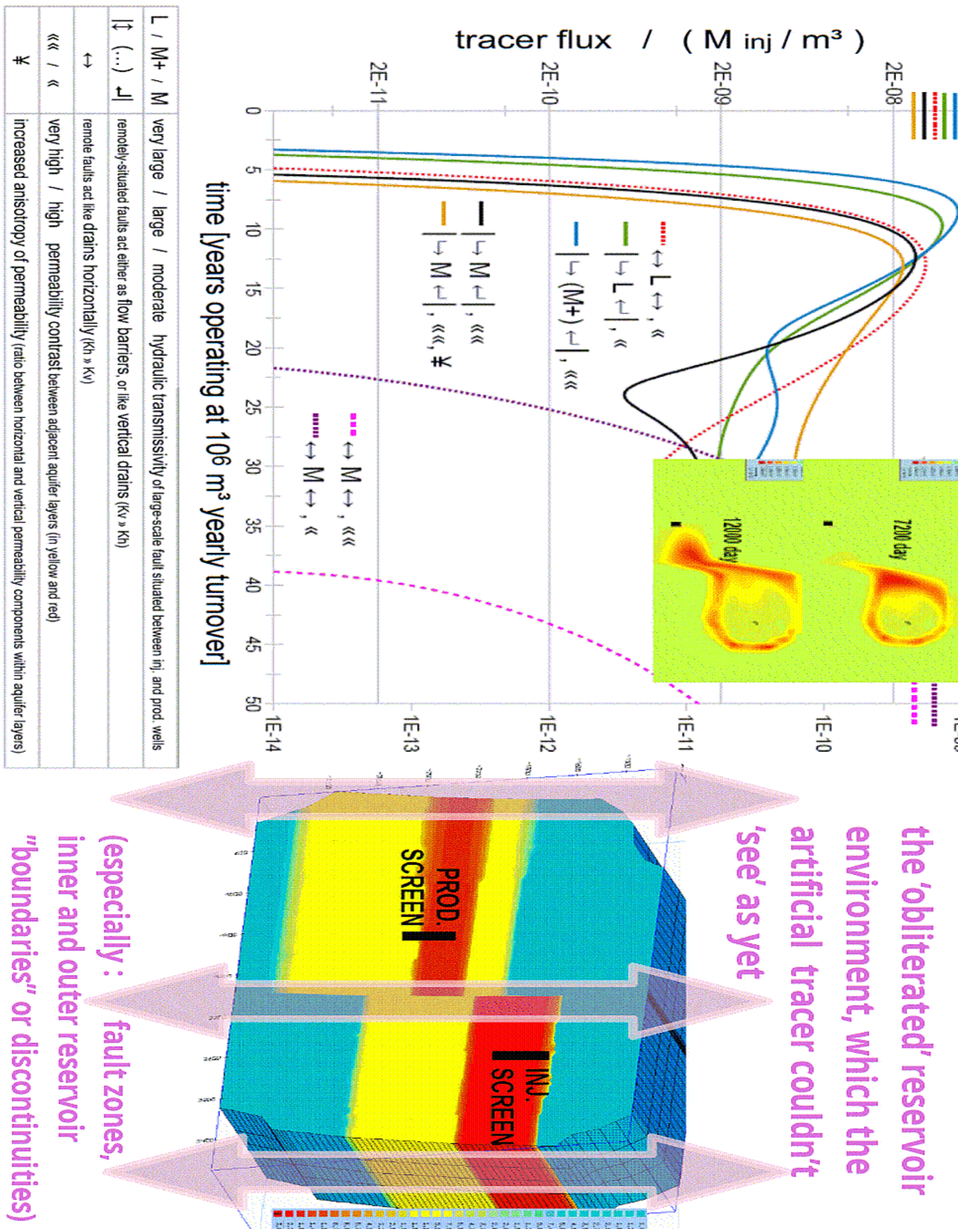


**Figure 7: A schematic representation of structural hydrogeology features of the reservoir (roughly simplified but largely resembling the first of two alternative conceptual models proposed by Meixner 2009) that are not captured by the early to mid-late tracer signal, and are furthermore unlikely to associate with major lithium 'replenishment' sources, for the particular reservoir under investigation in the Upper Rhine rift valley.**

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