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Stochastic Assessment of Land-Use Change Effect on Groundwater Quality

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1. Abstract

Assessing the impact of a land-use change (LUC) and associated changes in pollutant discharge on groundwater quality (nitrate, salinity) under heterogeneous aquifer conditions requires a complex analysis. Stochastic methods have been used to account for prediction uncertainty but at the cost of a high computational demand, which significantly limits the application of these approaches.

This study evaluates the application of a meta-analytical solution for evaluating the change in contaminant breakthrough curves at extraction wells as a result of a potential LUC. The solution uses the concentration percentiles from a reference stochastic simulation of water flow and solute transport in a groundwater system, assuming a specific (reference) land-use. The effect of any potential LUC is evaluated by scaling the ratio between the reference and the new (post-LUC) average pollutant discharge concentrations.

The validity of the proposed simple meta-analysis is tested by comparing the results of the meta-solution with those from a direct simulation of the post-LUC. Simulation results show that the accuracy of the meta-analytical solution increases when the average recharge rates for both pre- and post-LUC remain approximately unchanged.

Results indicate also that a potential change in the spatial variability of the recharge rate doesn't significantly impact the flow field, travel times, and the resulting concentrations; only a change of magnitude in recharge does.

2. Objective and Approach

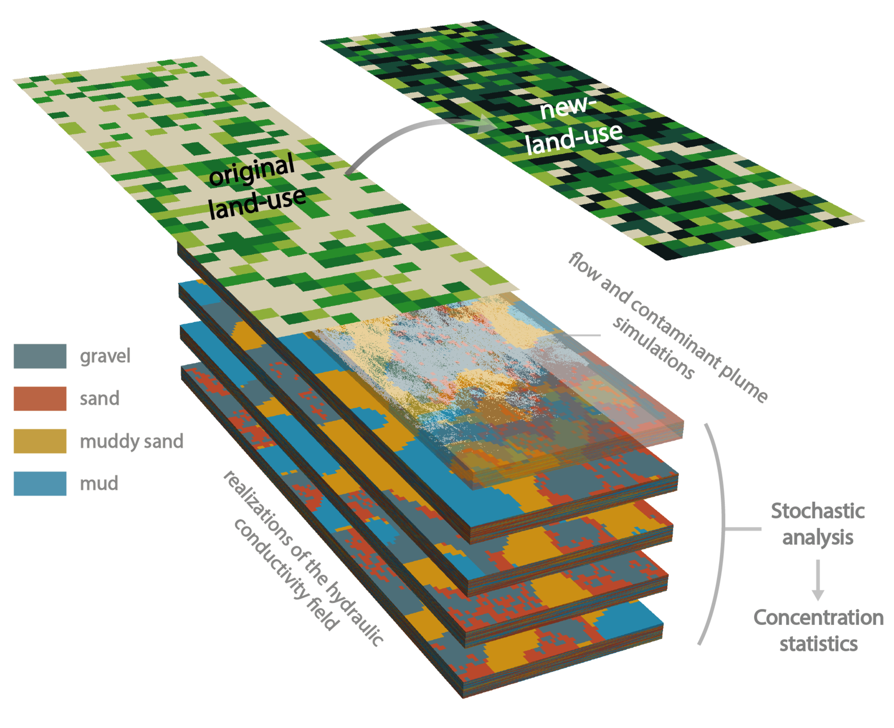


Figure 1: Illustration of a LUC stochastic assessment

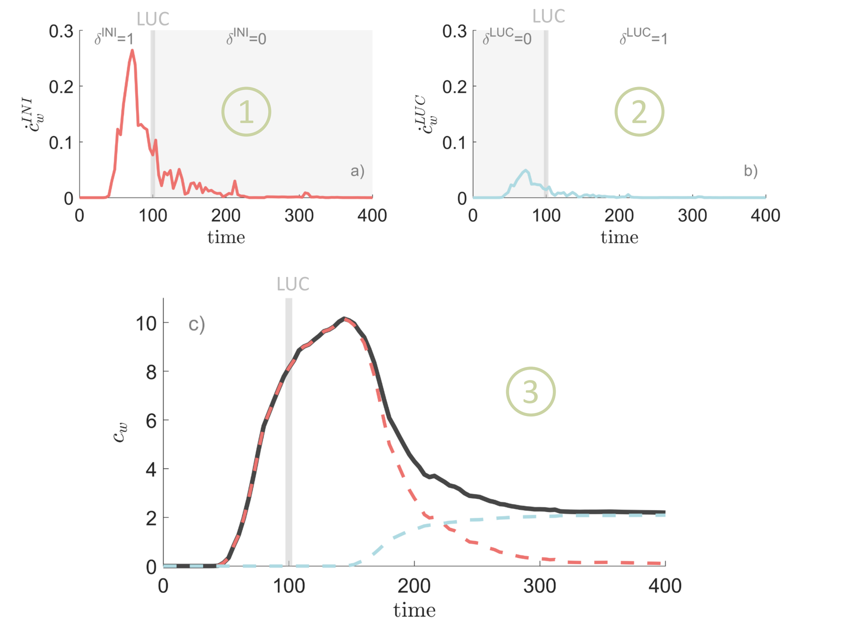


Figure 2: Illustration of the proposed scaling / convolution approach to estimate concentration signal after a LUC

Goal

Assessing the statistics of well concentrations resulting from a LUC without explicitly simulating flow and transport in a Monte Carlo (MC) framework

Proposed simple approach

1. Concentration statistics of an initial scenario are explicitly evaluated (MC) for a pulse injection of mass ($\dot{c}_w^{INI}$)
2. Estimation of well concentrations after a LUC ($\dot{c}_w^{LUC}$) by scaling initial well concentrations ($\dot{c}_w^{INI}$):

$$\dot{c}_w^{LUC}(t) = \dot{c}_w^{INI}(t).\frac{\sum_i k_i^{LUC}\bar{c}_i^{LUC}}{\sum_i k_i^{INI}\bar{c}_i^{INI}}$$

k_i^{LUC}: *proportion of the i^{th} crop*
$\bar{c}_i^{LUC}$: *average leaching concentration of the i^{th} crop*

3. Convolution to estimate signals from continuous injection :

$$c_w(t) = \int_0^t \dot{c}_w^{INI}(t-\tau).\delta^{INI}(\tau) + \int_0^t \dot{c}_w^{LUC}(t-\tau).\delta^{LUC}(\tau)$$

δ^{INI}: *delta function = 0 or 1 at all times before the LUC*
δ^{LUC}: *delta function = 0 or 1 at all times after the LUC*

4. Analyze concentrations stochastically

3. Validation

Assumptions

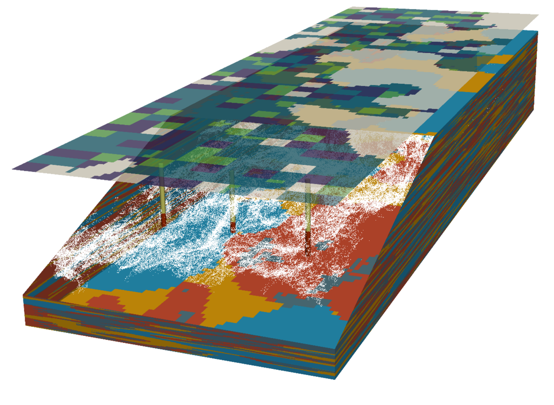
The step 2. of the proposed approach assumes a couple of key points:

- the spatial variability of leaching concentrations associated with a given crop over a basin does not significantly impact the amount of mass recovered at extraction wells at time *t*;
- a LUC does not significantly impact the transport pathways of the contaminant and the related travel times to a well.

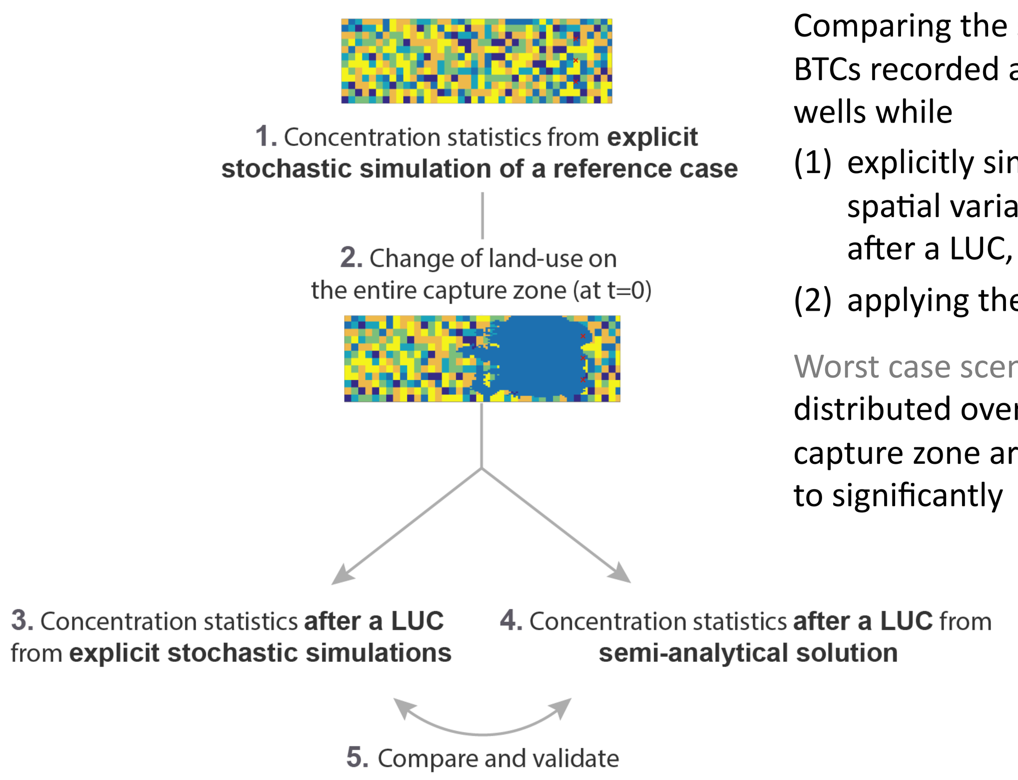
Reference case: Explicit stochastic simulation

Typical non-point source contamination by nitrate in the Central Valley, CA (USA)[1]; statistics of $\dot{c}_w^{INI}(t)$ obtained using:

- TPROGS[2] to describe the spatial variability in the hydraulic conductivity (50 realizations)
- Random distribution (uniform) of 6 crops (see 1. of scheme)
- Spatial variability of source terms (recharge and nitrate leaching) evaluated by a series of HYDRUS 1D[3] simulation
- Modflow 2000[4] to solve the flow
- RW3D[5] to solve the advective transport toward 3 wells



Testing approach



Comparing the statistic of contaminant BTCs recorded at a series of extraction wells while

(1) explicitly simulating the change in the spatial variability of source terms after a LUC, and
(2) applying the analytical solution in 2.

Worst case scenario: LUC where all crops distributed over the entire probable capture zone are changed into a single LU to significantly impact the flow field.

We test 2 cases, with different ratio of pre- ($\bar{r}^{INI}$) and post-LUC ($\bar{r}^{LUC}$) average recharge:

- a LUC preserving the average recharge (grape only, $\bar{r}^{LUC}/\bar{r}^{INI}$=1.02)
- a LUC significantly lowering average recharge (grain only , $\bar{r}^{LUC}/\bar{r}^{INI}$=0.76)

Results

The semi-analytical solution performs well when the average recharge rate isn't significantly changed by the LUC. Important to always keep track of $\bar{r}^{LUC}/\bar{r}^{INI}$.

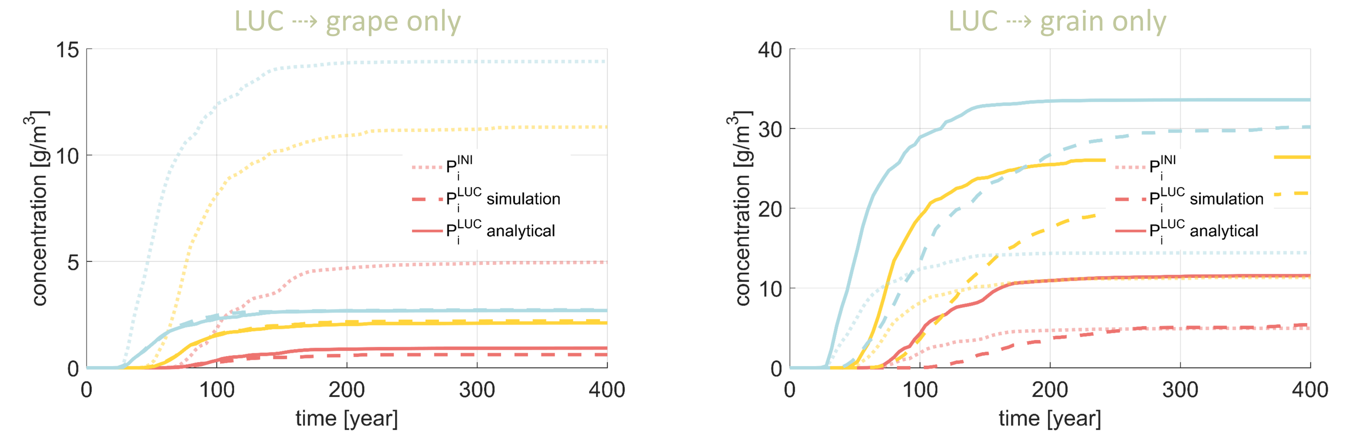


Figure 3: Concentration 10[th] (red), 50[th] (yellow), and 90[th] (blue) percentiles for the initial scenario from full stochastic simulations of flow and transport (dots), for the scenario with all crops located in the stochastic capture zone changed to grapes (left) or grain (right) from full stochastic simulations of flow and transport (dashes), and for a similar scenario outputs evaluated semi-analytically (plain lines).

4. Application | Illustration

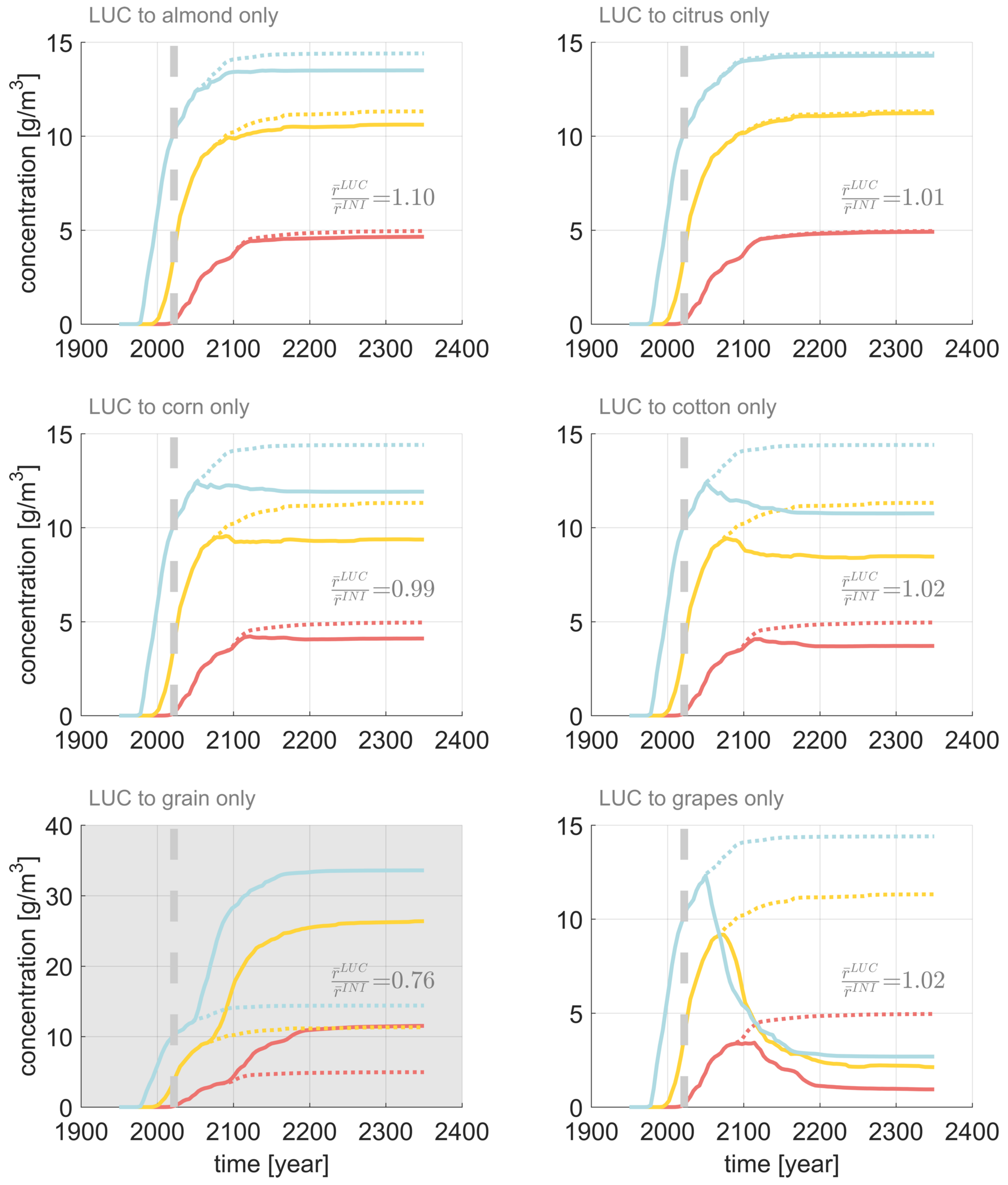


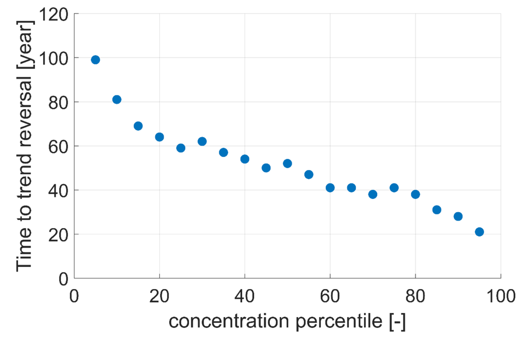
Figure 4: Concentration 10th (red), 50th (yellow) and 90th (blue) percentiles for a land use in the entire capture zone changed to only almond, citrus, corn, cotton, grain or grapes (plain lines). The vertical gray dashed line indicates the time at which the land-use change (LUC) occurs. A business as usual would produce concentration BTCs statistics shown in dotted lines.

Setting

- Use the reference case as initial scenario
- The first mass arrival of nitrate at the groundwater table occurs in 1950
- The land use over the entire probable capture zone is changed into a single crop in 2020

Outputs

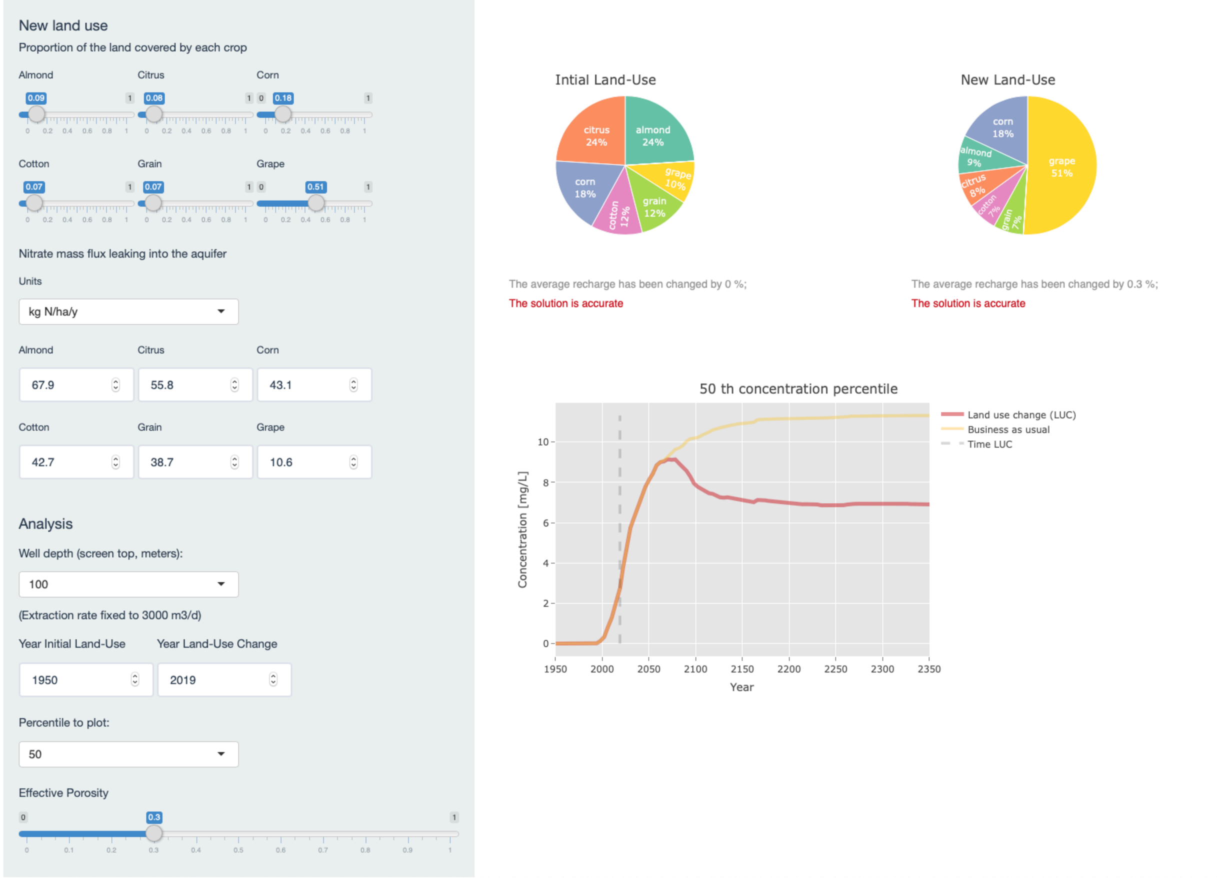
- The proposed method computes breakthrough percentiles virtually instantaneously
- In our setting, a LUC to grain is the only case leading to an unsatisfactory solution due to a significant change in the average recharge
- Time to trend reversal is lower for the higher concentration percentiles
- Good prospects of reducing relatively quickly the highest concentrations observed over a basin



5. Online tool

Try out the R-Shiny application here →
chrishenri.shinyapp.io/NPS_tool/

- Visualization of concentration statistics (matrix of exceedance probability, percentiles, histograms)
- Test land use change scenarios by specifying leaching nitrate mass flux and crop proportions pre- and post-LUC
- Specify years of initial and new land-use
- Different depth of well screens
- Specify effective porosity (for scaling of travel times)
- Systematically estimate $\bar{r}^{LUC}/\bar{r}^{INI}$ to evaluate the solution accuracy



References

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Acknowledgements

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