A multi-layer transient groundwater flow and transport model of the Crau aquifer using stable isotope tracers

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SYMCRAU

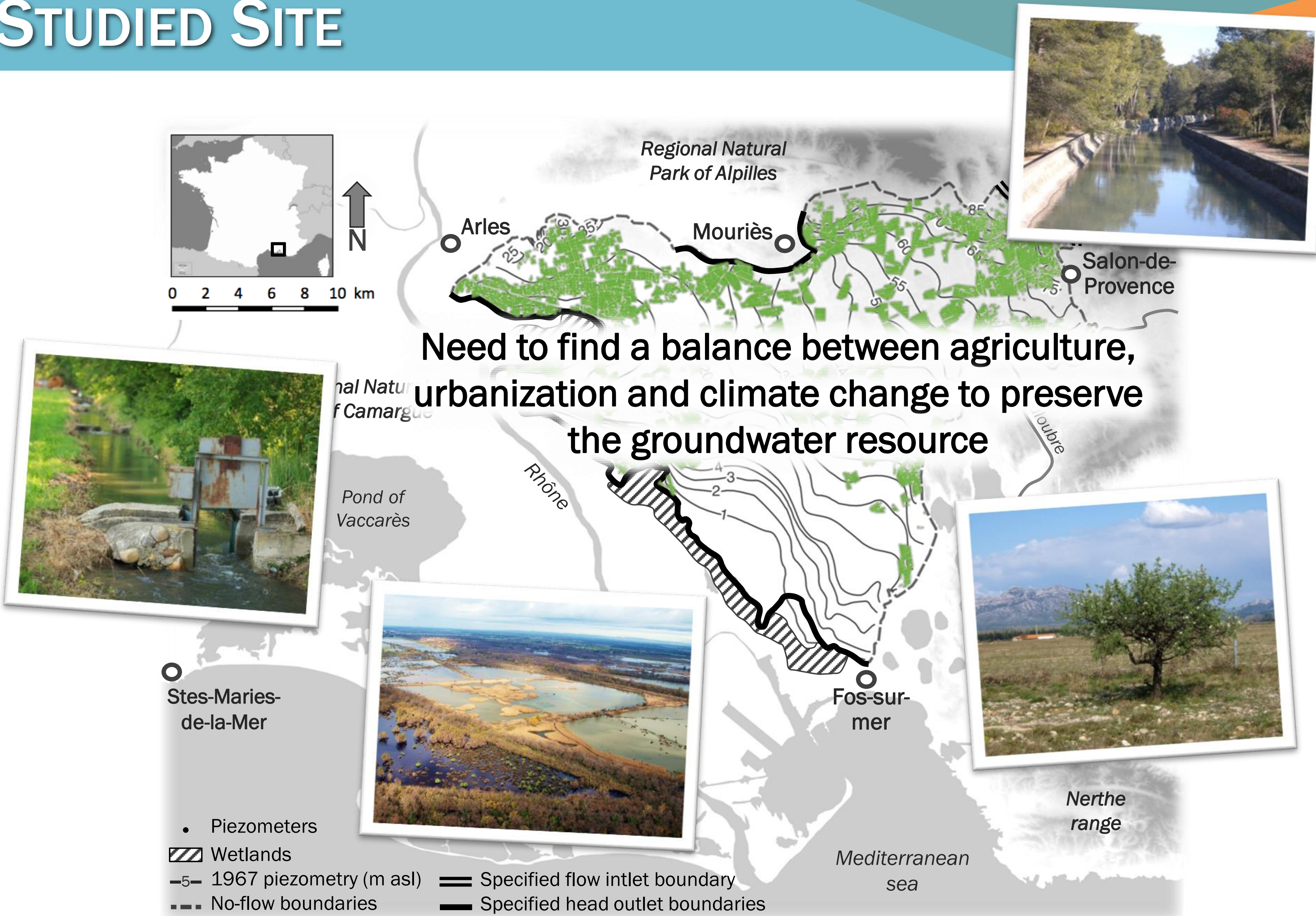
Géosciences de l'Environnement CEREGE Centre Européen de Recherche et d'Enseignement de Géosciences de l'Environnement

cnrs dépasser les frontières

Région PACA

Early Career Hydrogeologists' Network

Studied Site



Need to find a balance between agriculture, urbanization and climate change to preserve the groundwater resource

Objectives of the study

- Estimate the impacts of climate and land use changes on the groundwater resource
- Simulate the transport of pollutions or the salt-wedge propagation
- Approach:
  - Multi-layer model
  - Quantify the contribution of irrigation return flows to the recharge
  - Estimate specific yield
  - Calibrate the steady-state model
  - Reproduce the seasonality
  - Validate by simulating stable isotopes transport ($\delta^{18}O$, $\delta^{2}H$)

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Research papers

Partitioning groundwater recharge between rainfall infiltration and irrigation return flow using stable isotopes: The Crau aquifer

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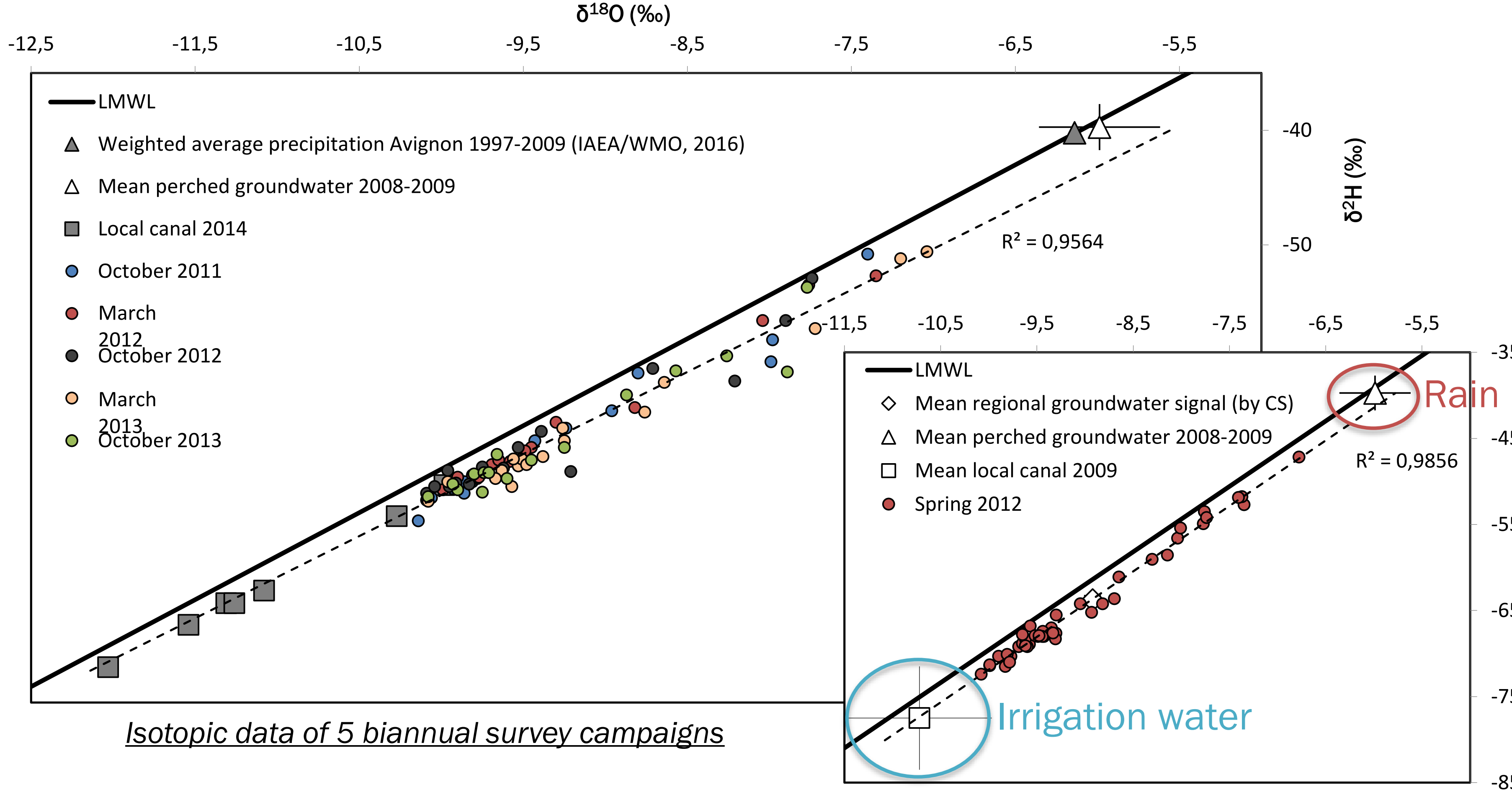
QUANTIFICATION OF THE MEAN AQUIFER RECHARGES

Séraphin, P., *et al.*
Partitioning groundwater recharge between rainfall infiltration and irrigation return flow using stable isotopes: The Crau aquifer. J. Hydrol. (2016),
http://dx.doi.org/10.1016/j.jhydrol.2016.09.005

Isotopic data



Isotopic data of 5 biannual survey campaigns

- Linear trend reflects a mixing between the two end-members contributing to groundwater recharge
- Able to implement this data in a parsimonious hydro-isotopic mixing model using geostatistics
  - Irrigation return flow (R_i) = 4.92 ± 0.89 $m^3 s^{-1}$, or 1109 ± 202 mm yr^1 (69 ± 9%)
  - Natural recharge (R_n) = 2.19 ± 0.85 $m^3 s^{-1}$, or 128 ± 50 mm yr^1 (31 ± 9%)

Estimation of the specific yield distribution

Water Table Fluctuation method

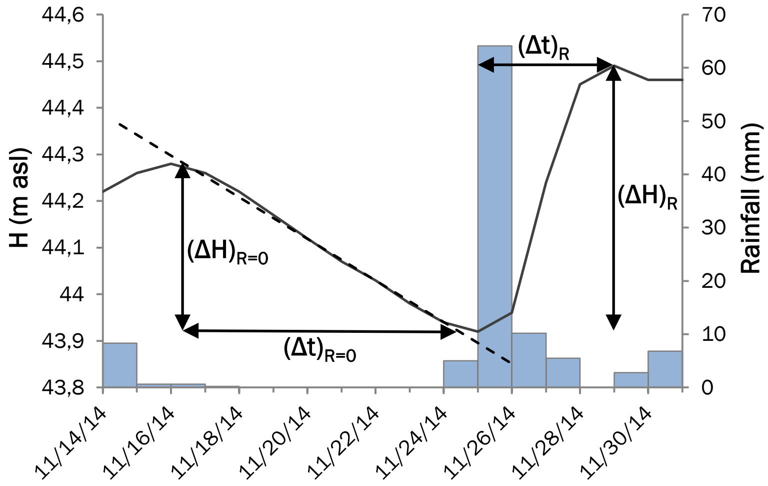
- Approach based on multiple interpretations of major infiltration events in term of specific yield:

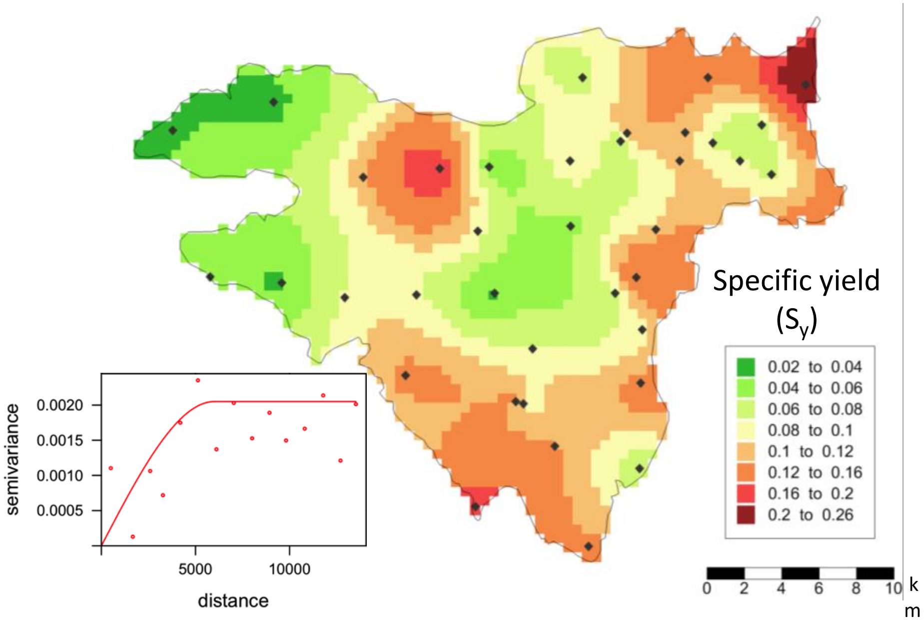
$$\left(\frac{\Delta H}{\Delta t}\right)_R S_y = P - (r + E + D)$$

- Assumptions:
  - Negligible runoff over Crau aquifer: r ≈ 0
  - Winter rainfall events: E ≈ 0
  - Estimation of net lateral drainage D

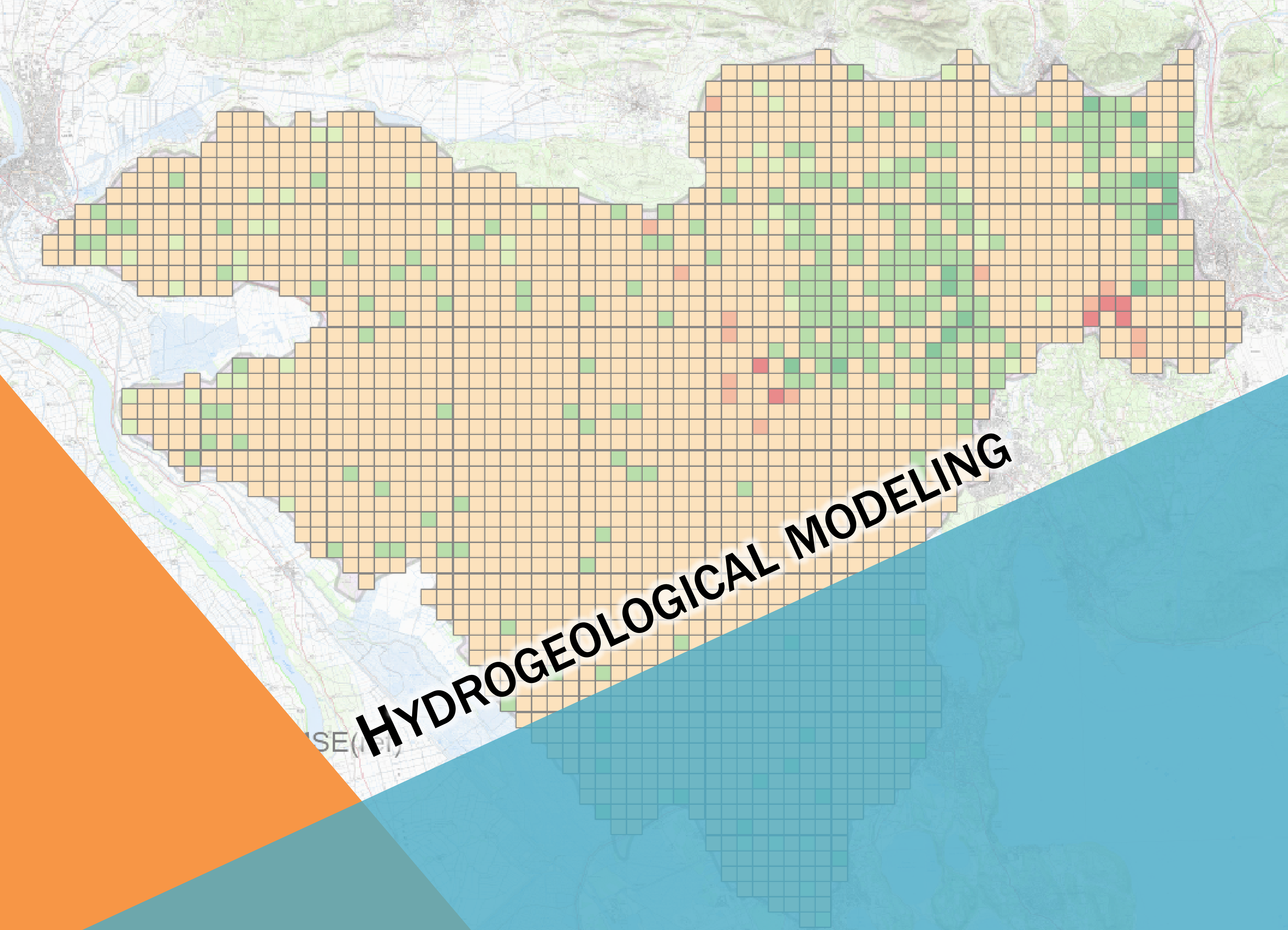
$$S_y = \frac{P}{\left(\frac{\Delta H}{\Delta t}\right)_R - \left(\frac{\Delta H}{\Delta t}\right)_{R=0}}$$

- Mean and SD of S_y interpreted for 31 piezometers



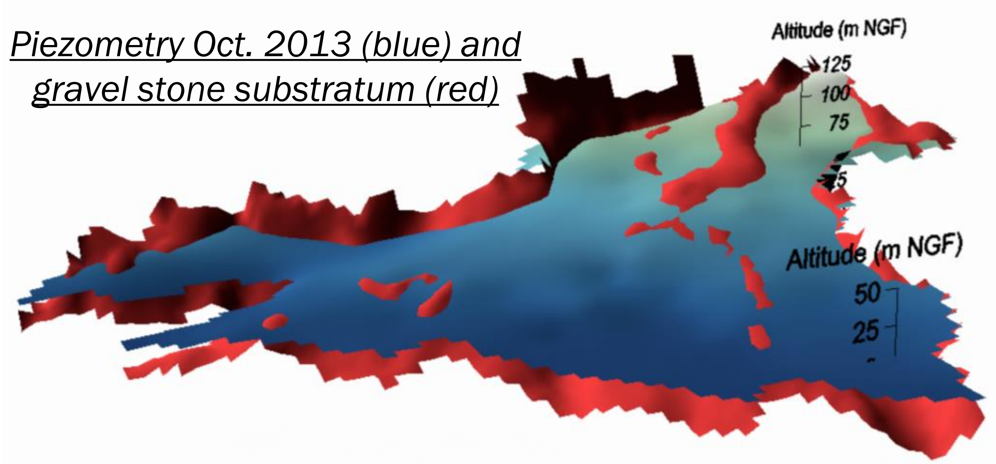


Hydrogeological Modeling

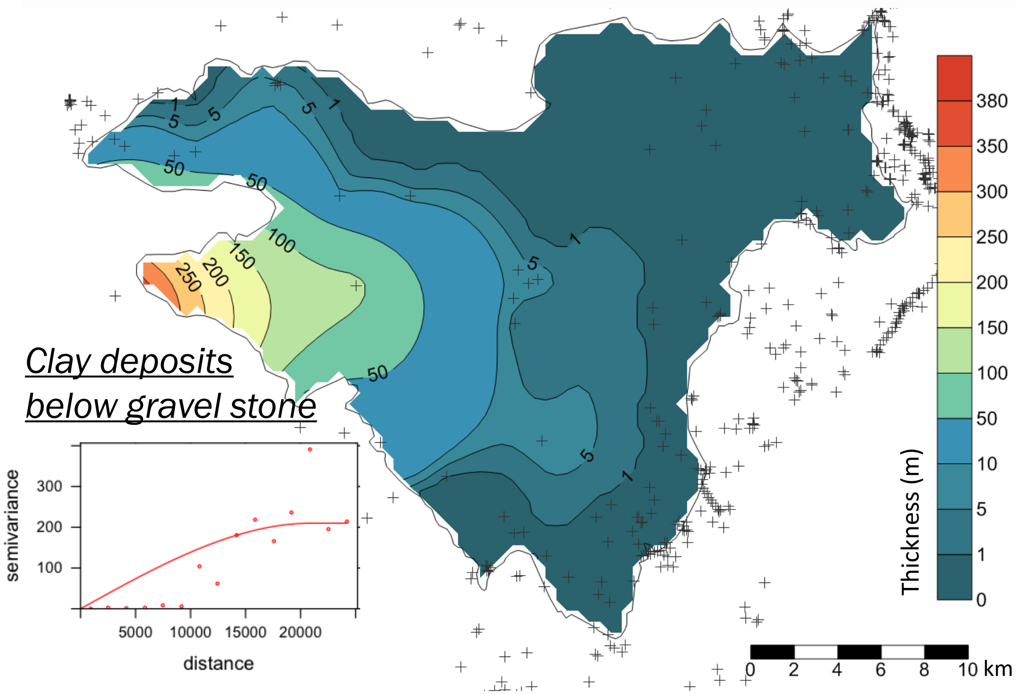


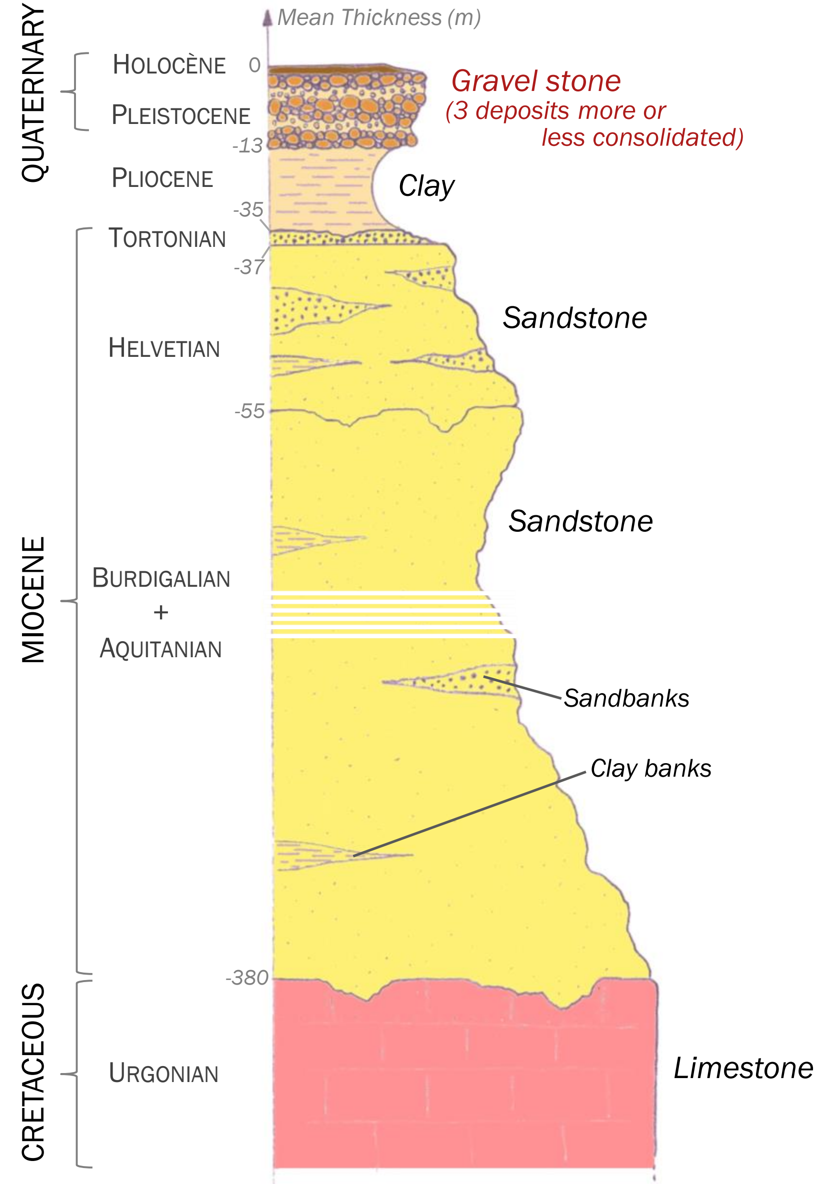
A new Geological model

Piezometry Oct. 2013 (blue) and gravel stone substratum (red)

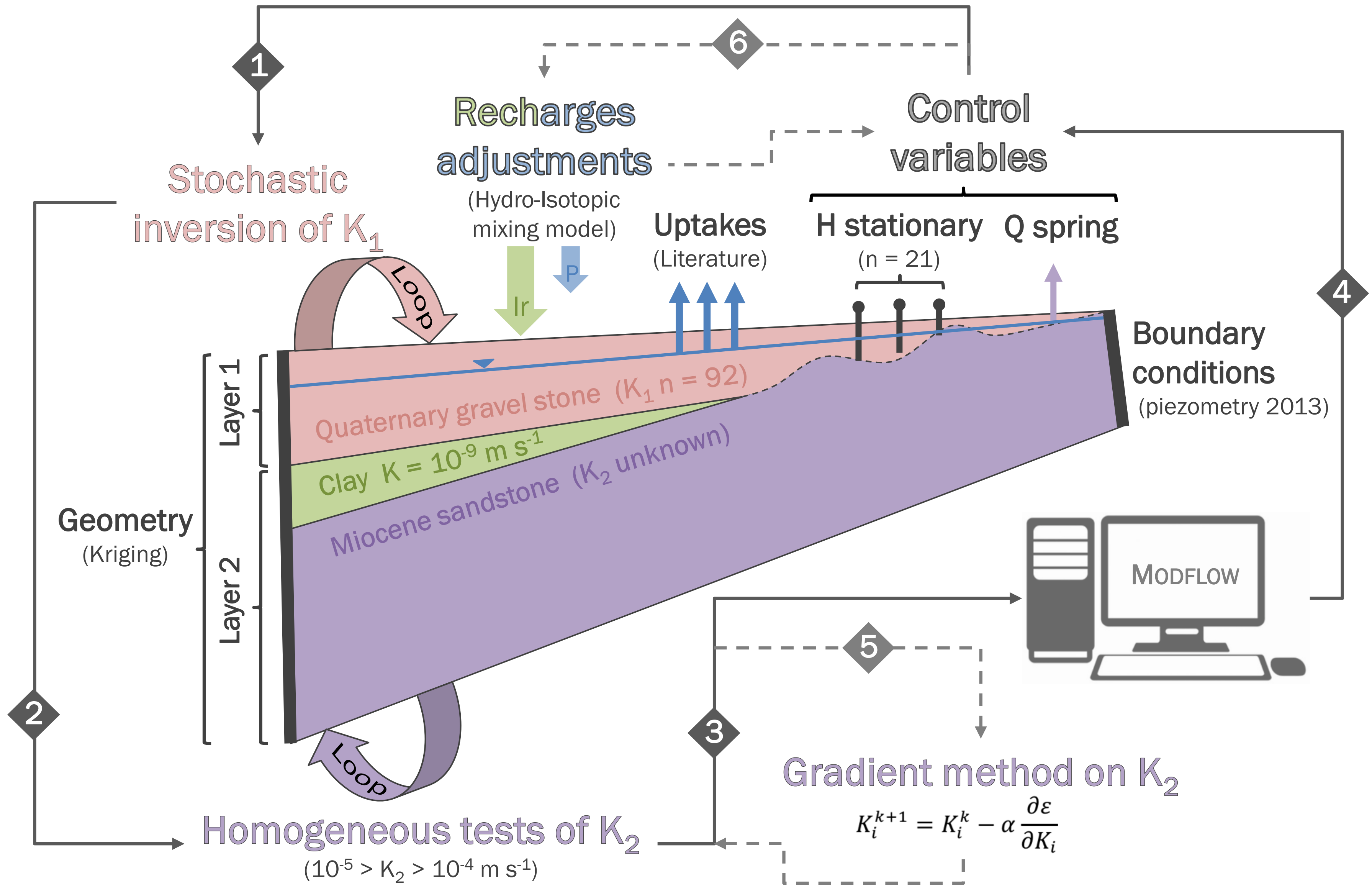


Clay deposits below gravel stone



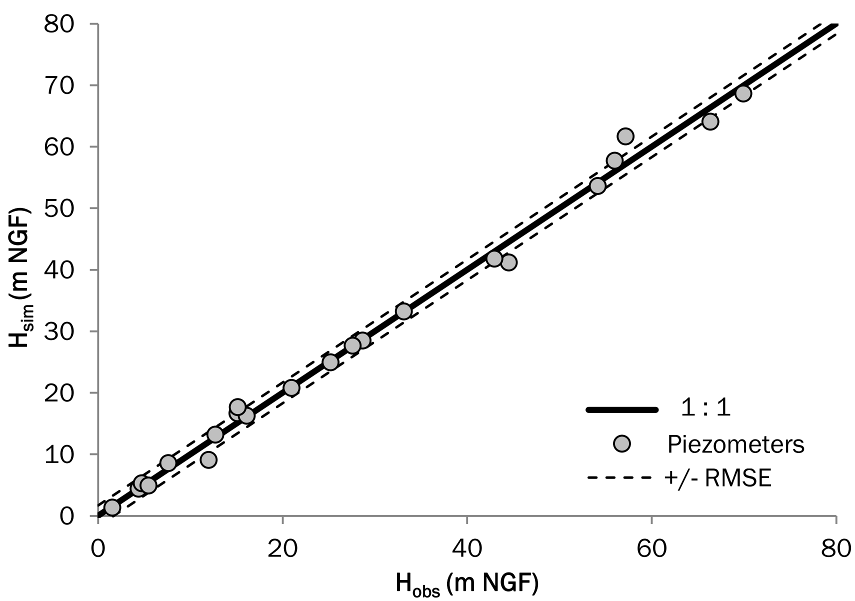


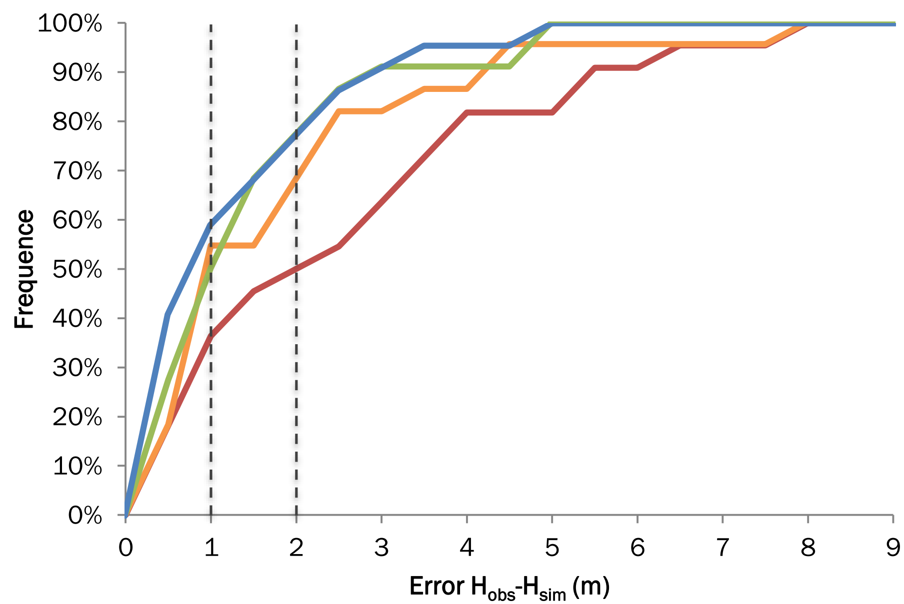
CALIBRATION OF THE STEADY STATE MODEL



RESULTS OF STEADY-STATE MODEL

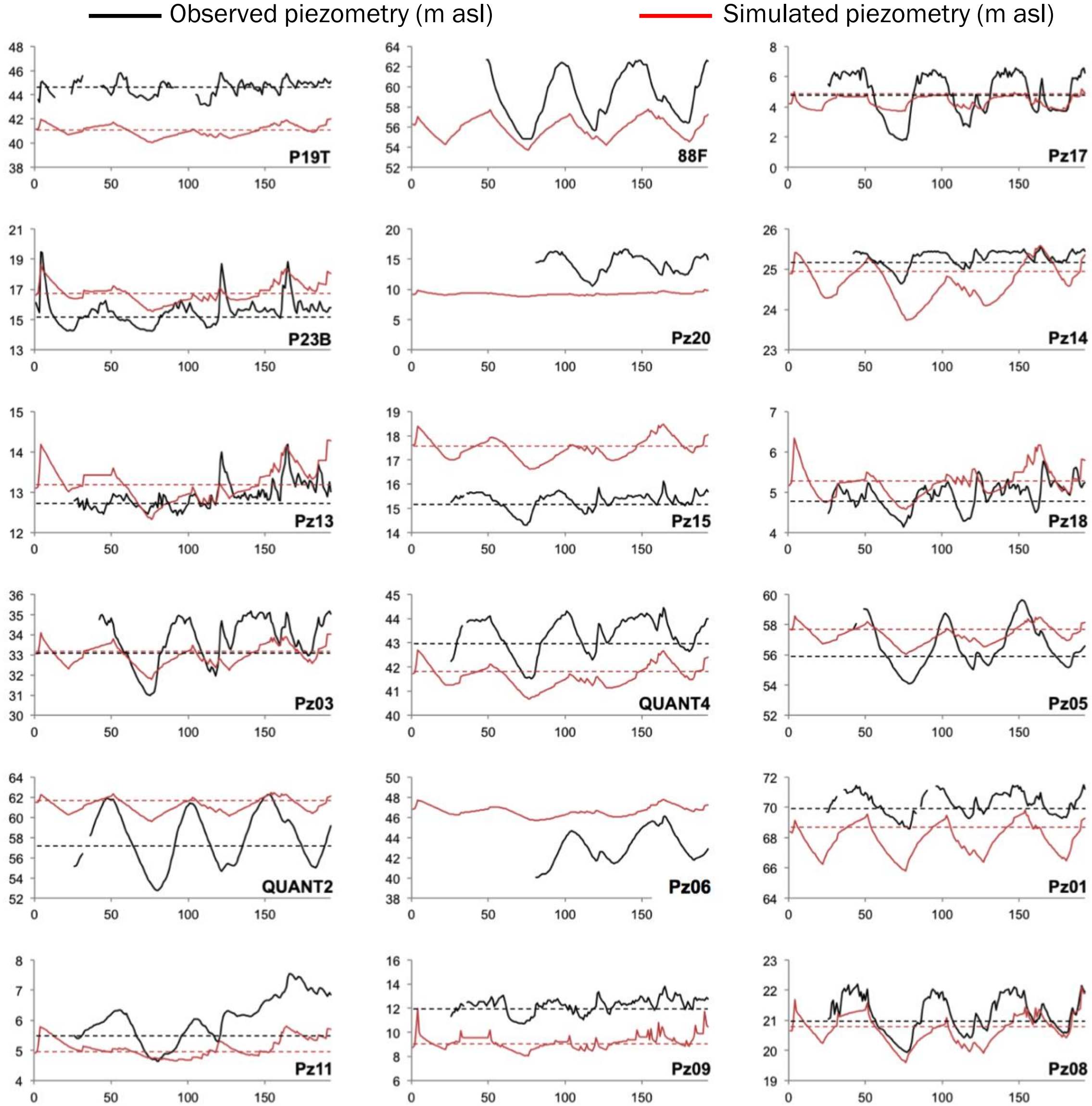
- Reference simulation (red)
  - *Error = 2.47 m ; RMSE = 3.25 m*
- Stochastic inversion of the permeability of both layer (orange)
  - *Error = 1.69 m ; RMSE = 2.49 m*
- Gradient method to locally adjust the bottom layer permeability (green)
  - *Error = 1.37 m ; RMSE = 1.87 m*
- Recharges final adjustment: R_n = 84 mm an^{-1} et R_i = 1212 mm an^{-1} (Blue)
  - *Error = 1.15 m ; RMSE = 1.67 m*





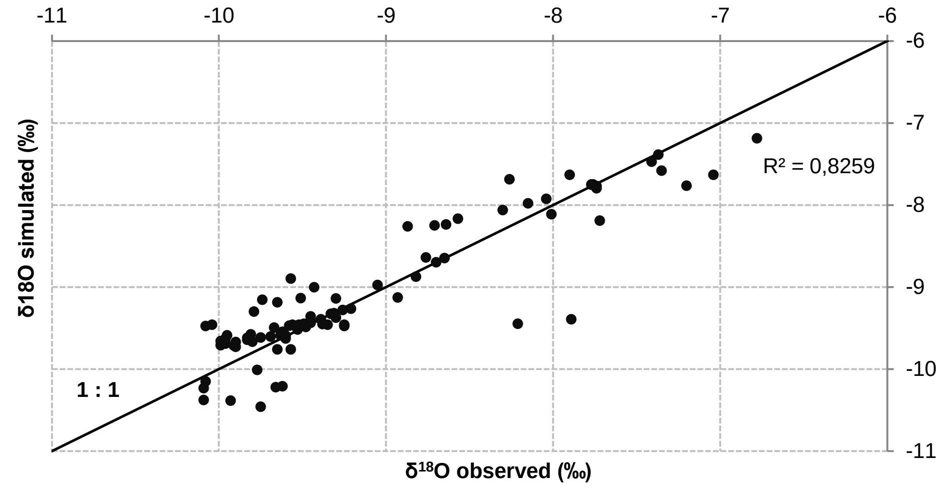
RESULTS OF TRANSIENT MODEL

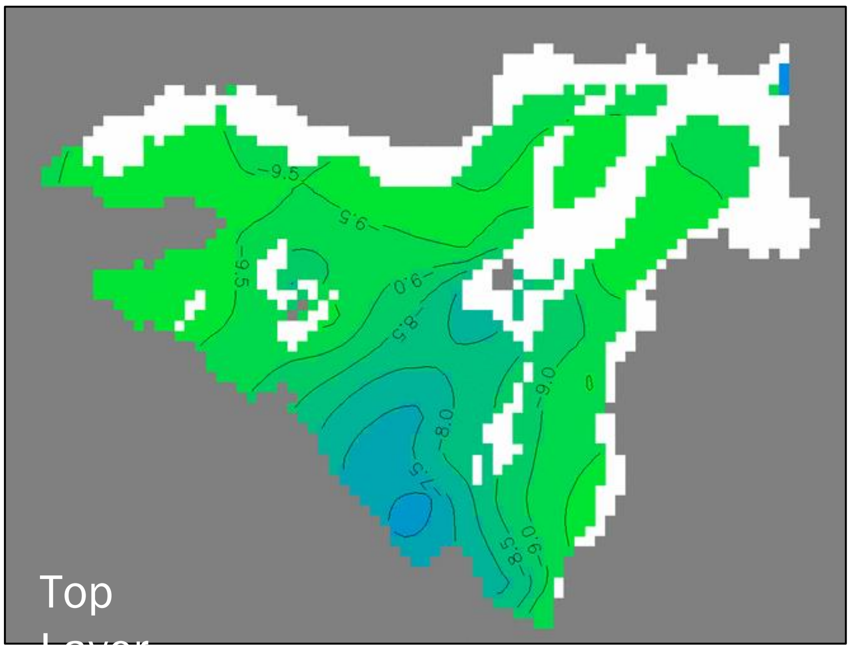
- Timing of seasonality
  - *Respecting irrigation periods and rainfall events*
- Vertical offsets
  - *Errors inherited from the steady-state model (dashed lines: red = simulated ; black observed)*
- Amplitudes miss estimations
  - *Mainly caused by the use of a regional average value of the recharge by irrigation return flow (variable from one meadow to another)*

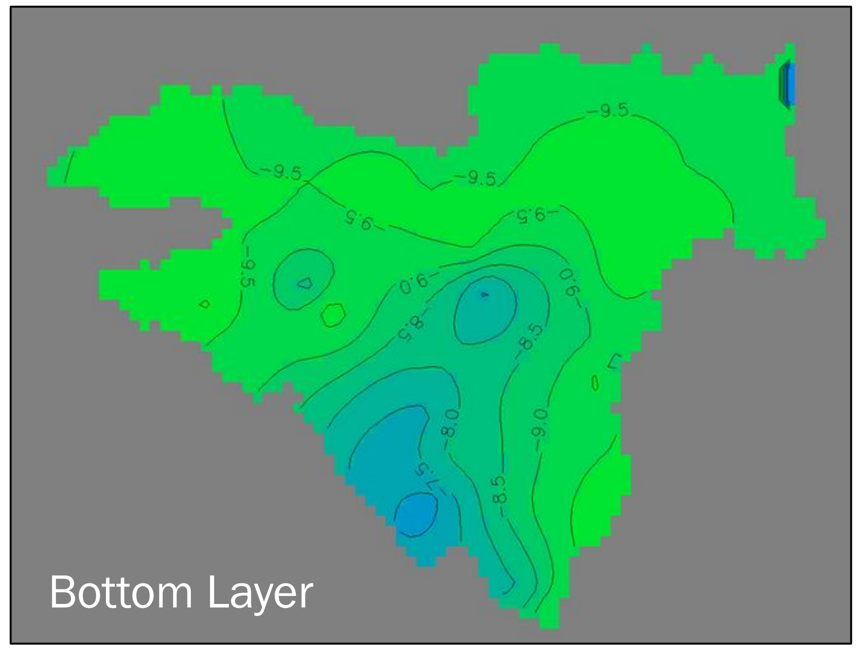


STABLE ISOTOPES TRANSPORT

- 2.5 years of simulations (advection/dispersion)
  - *Initial signal: the spring 2012 observed map for both layers*
- Signal more spatially contrasted than temporally
  - *Spatial distribution constant for 10 years*

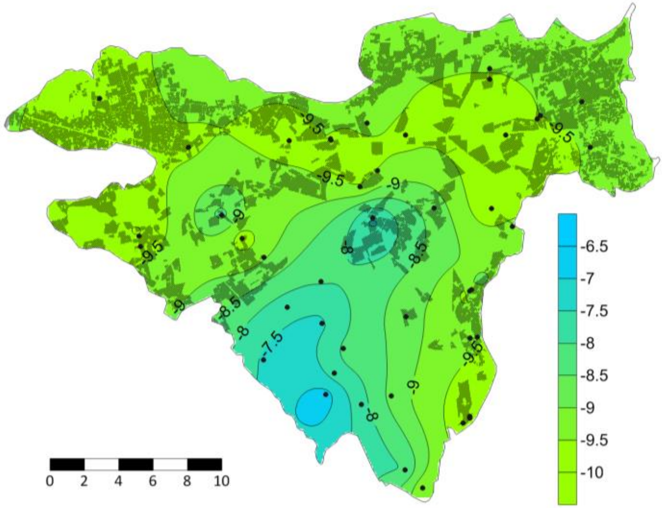


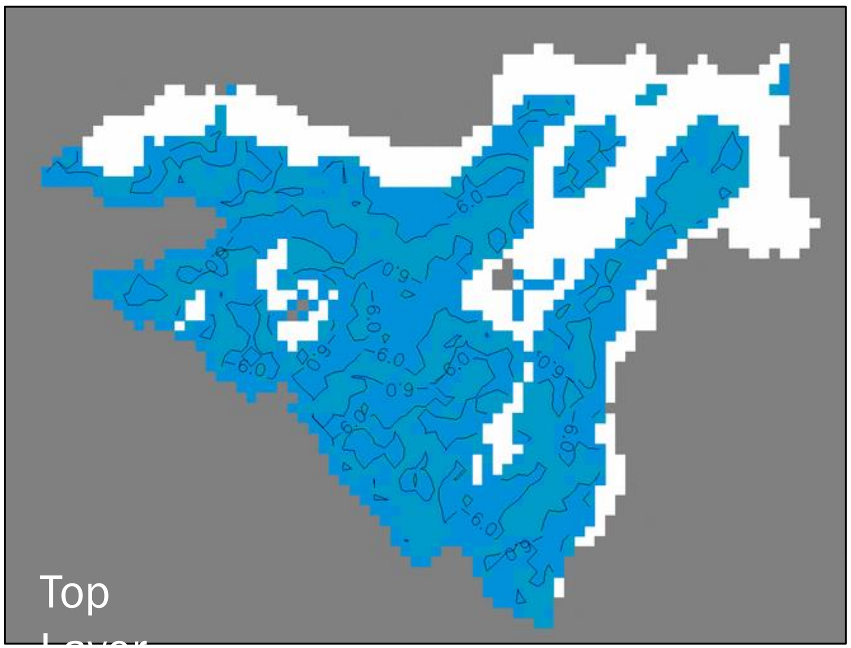


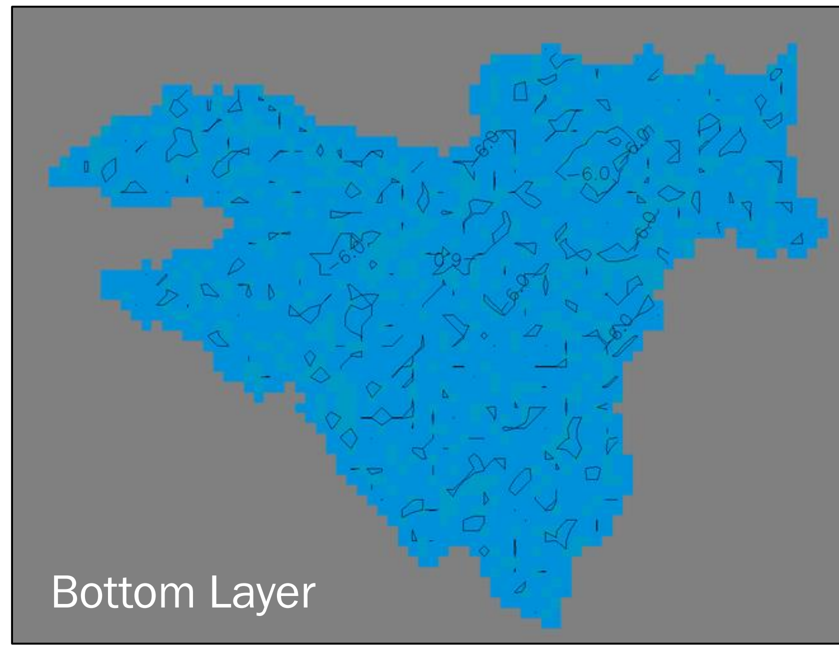


STABLE ISOTOPES TRANSPORT

- 500 years of simulation, starting before the creation of irrigated meadows
  - *Initial signal: natural recharge end-member (-6.00‰) for both layers*
  - *Uptakes only for the last century (Industrial revolution)*
  - *Meadows on the south-east part only for the last century*

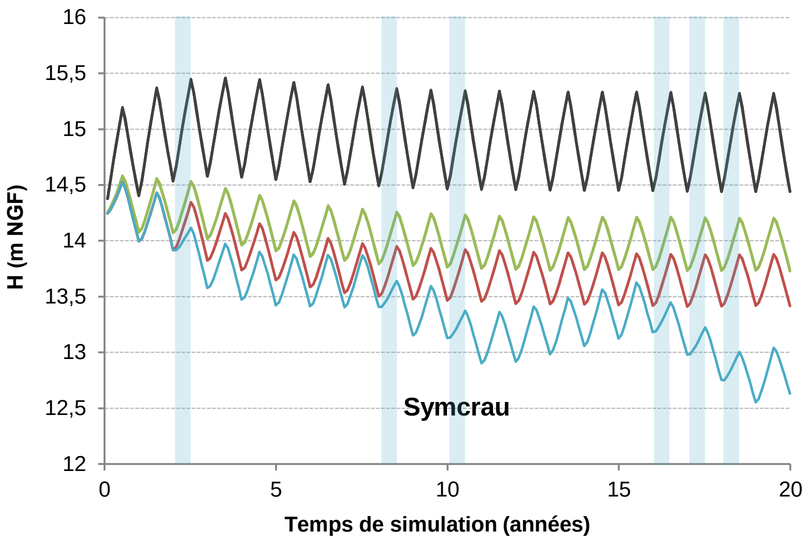






IMPACTS AND CONCLUSIONS

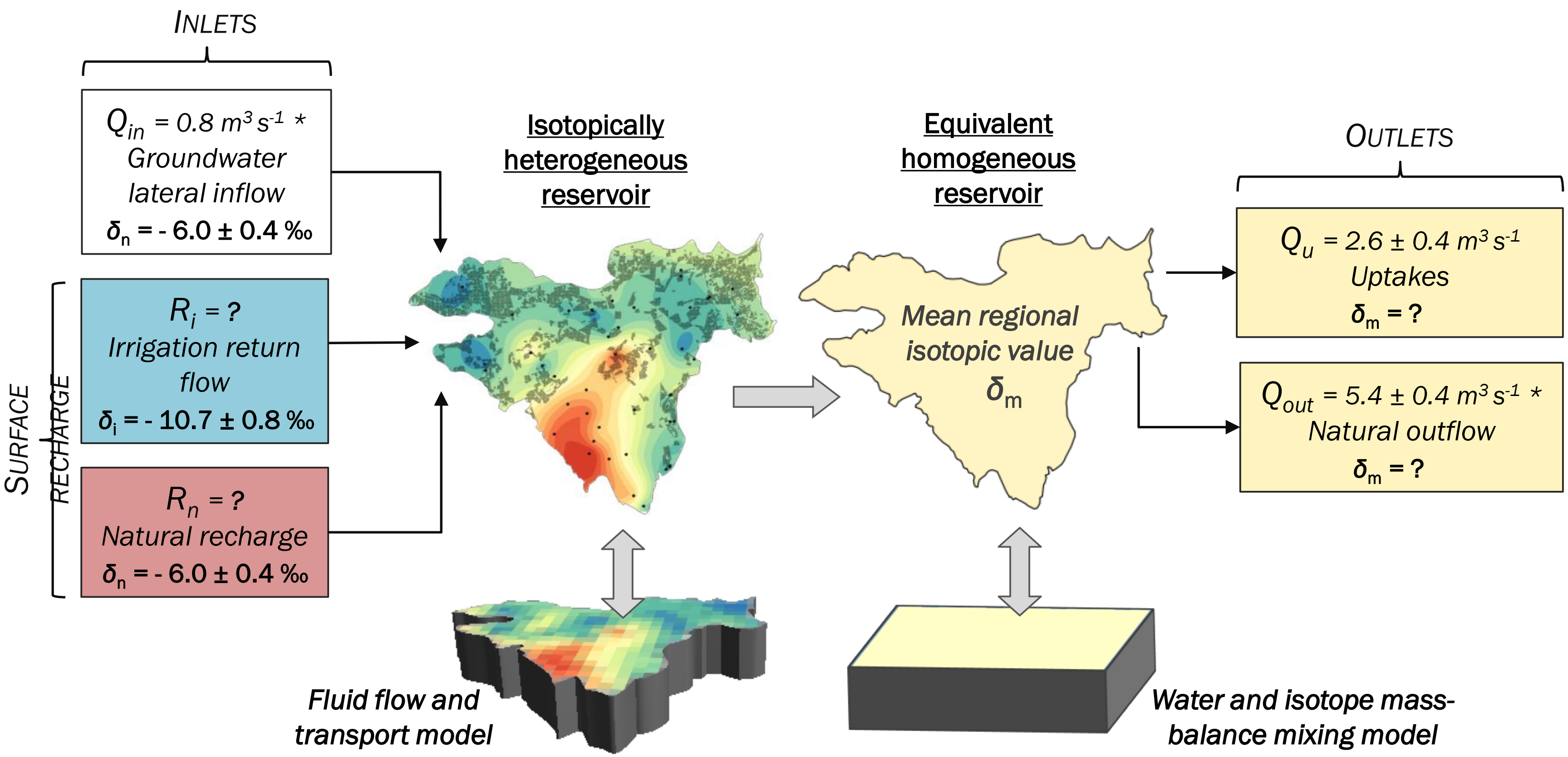
- Cumulated impacts of 2020-2040 scenarios :
  - Reference (Black)
  - Reduction of meadow surfaces by land-use planning:
    - *-5 km^2 out of 140 km^2 (Green)*
  - Global warming (IPCC AR5, 2014)
    - *-8% of rainfall, RCP 8.5 (Red)*
  - Simulation of water crisis:
    - *-20% of irrigation water input (Blue)*



- Conclusions of the modeling
  - Strong impact of irrigation return flow reduction on water table levels (up to 2 m)
  - Protected wetlands risk to be dried in few years
  - Parameters and variables estimated independently from any hydrogeological model
  - Steady-state model respecting the water budget with a mean piezometric precision of about 1 m
  - Transient model validated by simulating long term transport of stable isotopes
  - Need to introduce spatial distribution of the irrigation return flow

THANK YOU FOR YOUR ATTENTION

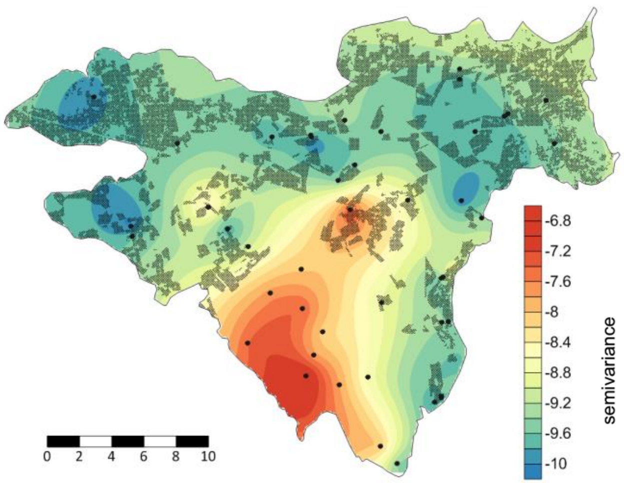
HYDRO-ISOTOPIC MIXING MODEL



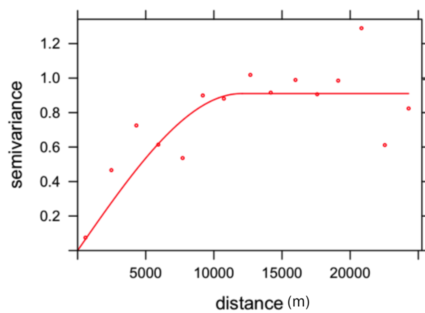
Water mass balance equation : $Q_u + Q_{out} = R_i + R_n + Q_{in}$

Hydro-isotopic mass balance equation : $\delta_m (Q_u + Q_{out}) = \delta_i R_i + \delta_n (R_n + Q_{in})$

GEOSTATISTICAL APPROACH

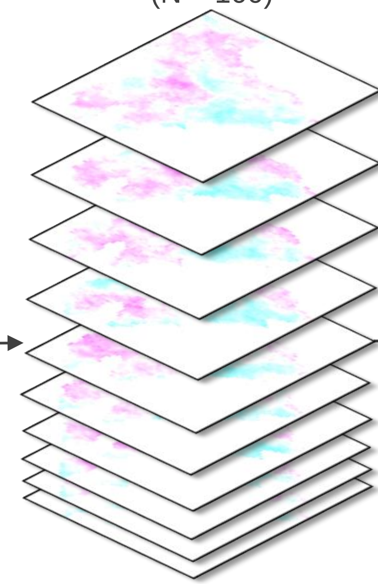


Variogram of Spring 2012 $\delta^{18}O$ data



Sequential Gaussian Simulations (SGS)

(N = 100)



100 simulated values of δ_m

Mean and **Standard deviation**

Irrigation return flow: $R_i = \left(\frac{\delta_m - \delta_n}{\delta_i - \delta_n}\right)(Q_{out} + Q_u)$

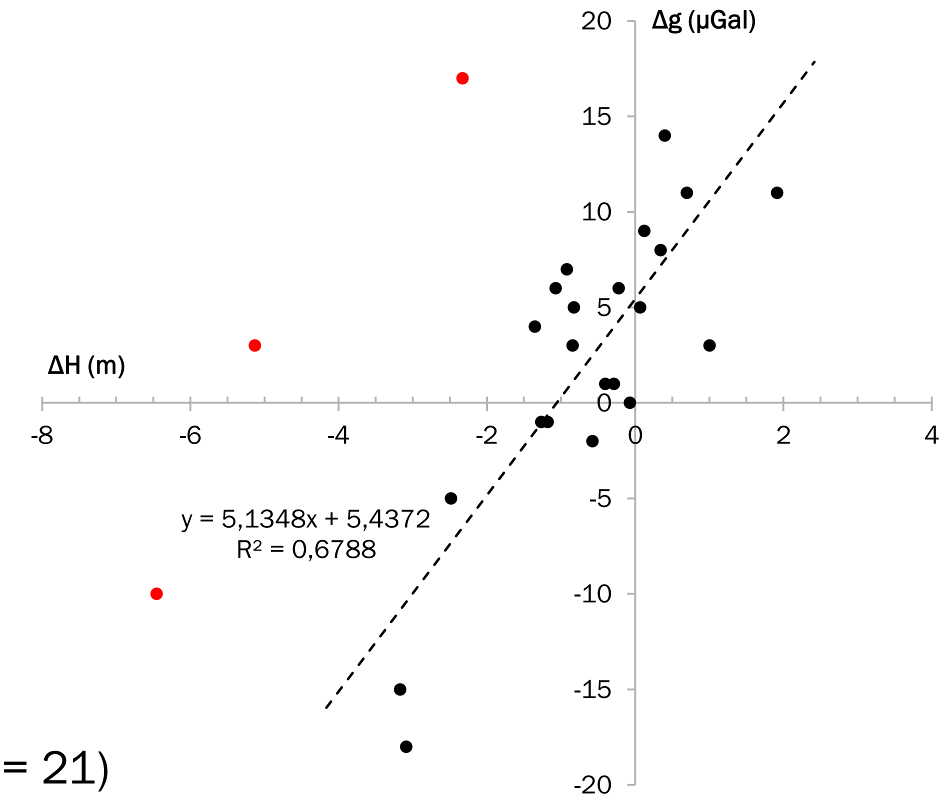
$$\sigma_{R_i}^2 = \left(\frac{\partial R_i}{\partial \delta_m}\right)^2 \sigma_{\delta_m}^2 + \left(\frac{\partial R_i}{\partial Q_u}\right)^2 \sigma_{Q_u}^2 + \left(\frac{\partial R_i}{\partial Q_{out}}\right)^2 \sigma_{Q_{out}}^2 + \left(\frac{\partial R_i}{\partial \delta_n}\right)^2 \sigma_{\delta_n}^2 + \left(\frac{\partial R_i}{\partial \delta_i}\right)^2 \sigma_{\delta_i}^2$$

Natural recharge: $R_n = \left(\frac{\delta_m - \delta_i}{\delta_n - \delta_i}\right)(Q_{out} + Q_u) - Q_{in}$

$$\sigma_{R_n}^2 = \left(\frac{\partial R_n}{\partial \delta_m}\right)^2 \sigma_{\delta_m}^2 + \left(\frac{\partial R_n}{\partial Q_u}\right)^2 \sigma_{Q_u}^2 + \left(\frac{\partial R_n}{\partial Q_{out}}\right)^2 \sigma_{Q_{out}}^2 + \left(\frac{\partial R_n}{\partial \delta_n}\right)^2 \sigma_{\delta_n}^2 + \left(\frac{\partial R_n}{\partial \delta_i}\right)^2 \sigma_{\delta_i}^2$$

HYDRO-GRAVIMETRIC APPROACH

- Two gravimetric surveys (high and low water table elevation)
- Bouguer anomaly: $\Delta g = 2\pi\rho G \, \Delta w$
  - with $\Delta \mathrm{w} = \Delta \mathrm{H} \, \mathrm{S_y} + \Delta S$ (Stock unsaturated zone)



- Regional specific yield = 12.3 ± 2% (n = 21)
- <u>Consistent with the WTF approach</u> = 10.1% (n = 21)