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PACA

# A MULTI-LAYER TRANSIENT GROUNDWATER FLOW AND TRANSPORT MODEL OF THE CRAU AQUIFER USING STABLE ISOTOPE TRACERS

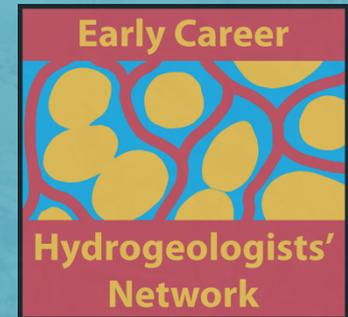
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43<sup>rd</sup> IAH  
CONGRESS

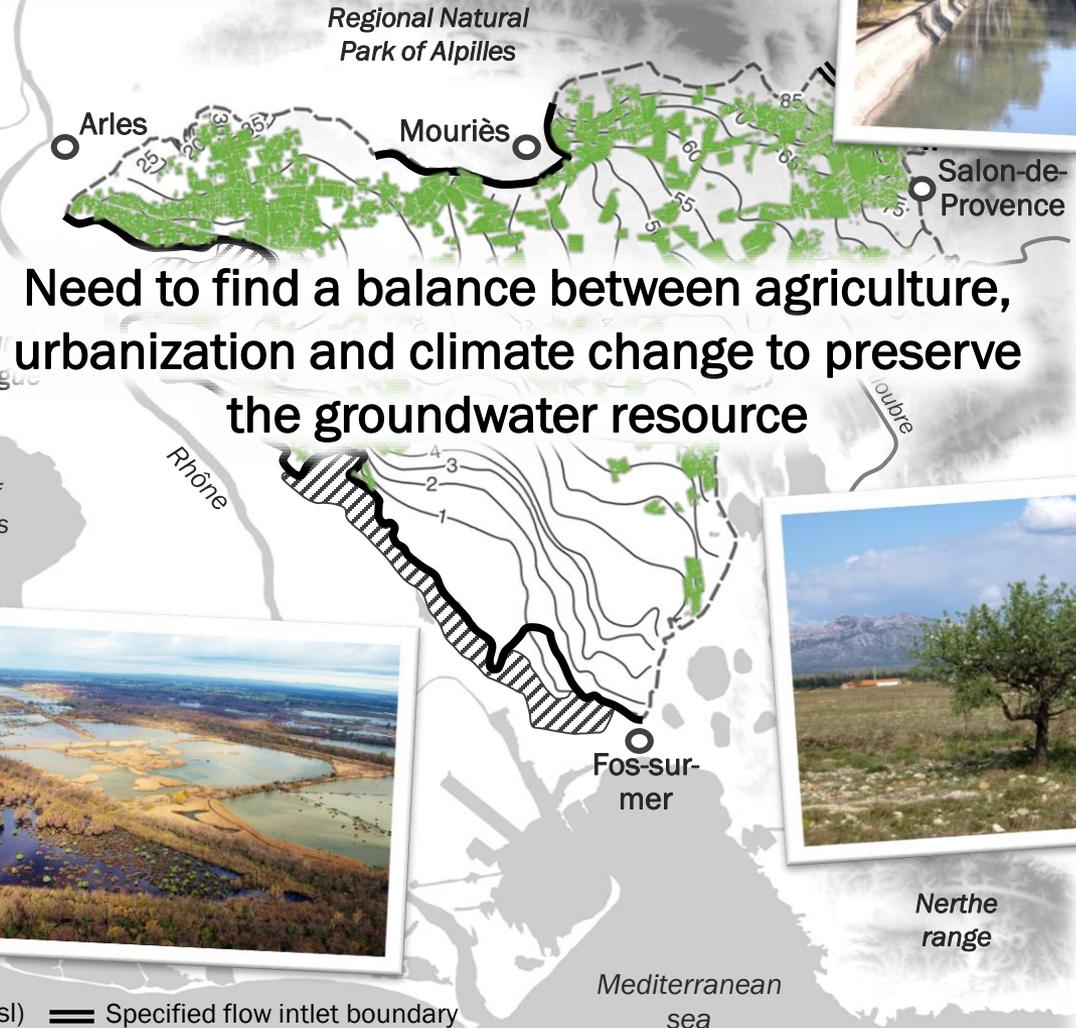
28/09/2016



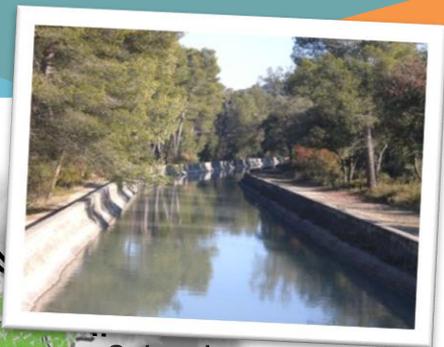
# STUDIED SITE



0 2 4 6 8 10 km



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



Pond of Vaccarès



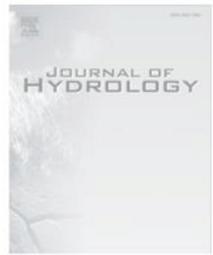
Nerthe range

○ Stes-Maries-de-la-Mer

- Piezometers
- ▨ Wetlands
- 5- 1967 piezometry (m asl)
- - - No-flow boundaries
- == Specified flow inlet boundary
- == Specified head outlet boundaries

# 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 ( $\delta^{18}\text{O}$ ,  $\delta^2\text{H}$ )



Research papers

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

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ABSTRACT

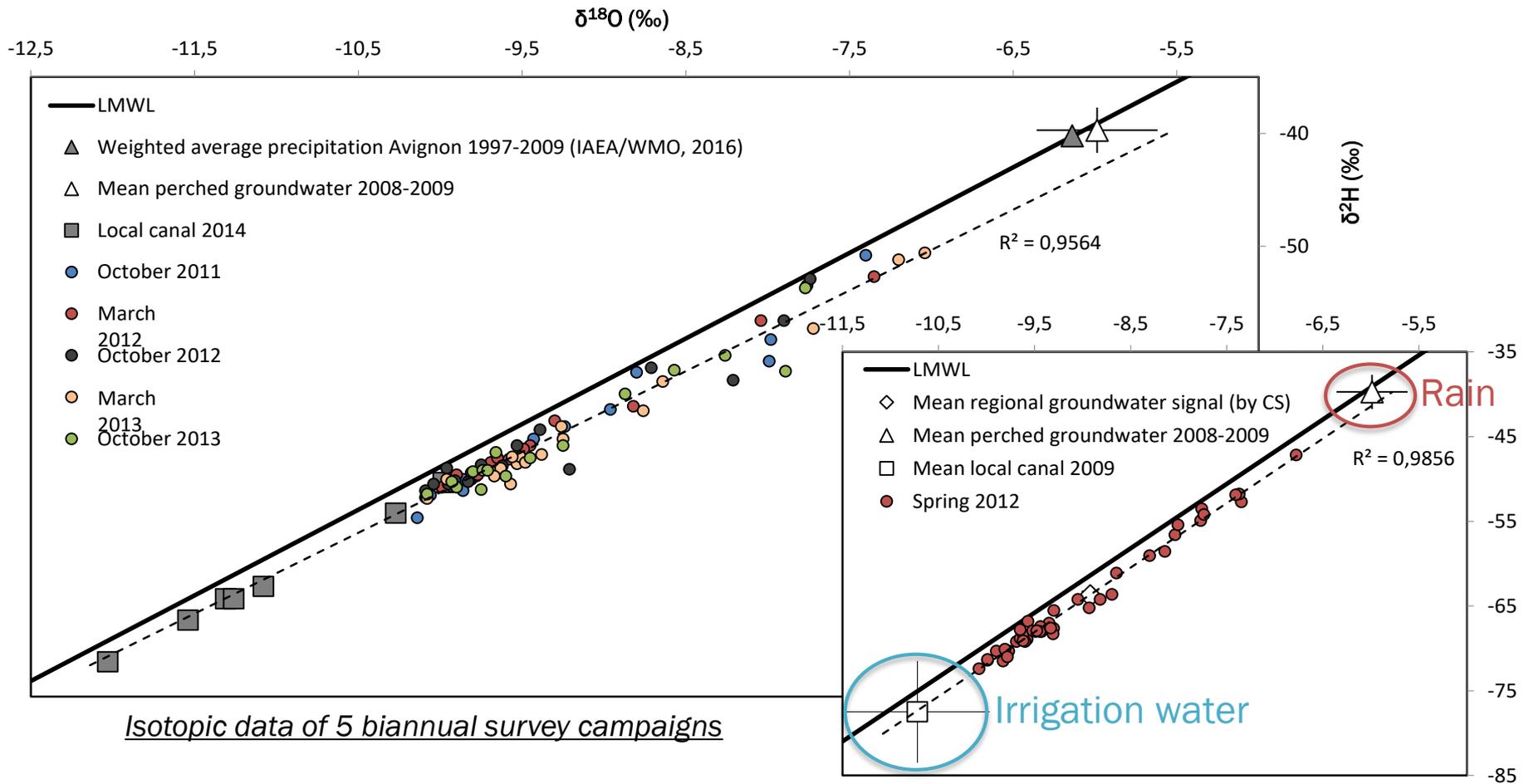
This study reports the assessment of the groundwater budget of the Crau aquifer (Southern France), which is poorly referenced in the literature. In this region, groundwater is naturally recharged by rainfall infiltration and isogenically controlled by a traditional irrigation practice, this allowing the aquifer to require a constant quantification of the groundwater mass balance in order to ensure a sustainable water management in the region. In view of the high isotopic contrast between natural recharge (rainfall infiltration) and local precipitation, stable isotopes of water can be used as conservative tracers to assess their contributions to the surface recharge. Extensive groundwater sampling was performed to obtain  $\delta^{18}O$  and  $\delta^2H$  over the whole aquifer. Based on a new piezometric contour map, combined with an updated aquifer geometry, the isotopic data were implemented in a geostatistical approach to produce a conceptual equivalent homogeneous recharge model. The isotopic compositions of the two end-members (natural recharge and irrigation return flow) were used to implement a parsimonious water and isotope mass-balance mixing model. The isotopic compositions of the two end-members were used to calculate the two recharge fluxes (natural recharge and irrigation return flow). The natural recharge is estimated to be 2.15 km<sup>3</sup> year<sup>-1</sup> and the irrigation return flow is estimated to be 1.6 km<sup>3</sup> year<sup>-1</sup>. The total recharge is 3.75 km<sup>3</sup> year<sup>-1</sup>. The natural recharge is caused by irrigation return flow. This study constitutes a first step toward a groundwater mass balance and a groundwater model of the Crau aquifer.

**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>



- 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 ( $R_i$ ) =  $4.92 \pm 0.89 \text{ m}^3 \text{ s}^{-1}$ , or  $1109 \pm 202 \text{ mm yr}^{-1}$  ( $69 \pm 9\%$ )
  - Natural recharge ( $R_n$ ) =  $2.19 \pm 0.85 \text{ m}^3 \text{ s}^{-1}$ , or  $128 \pm 50 \text{ mm yr}^{-1}$  ( $31 \pm 9\%$ )



**ESTIMATION OF THE SPECIFIC YIELD  
DISTRIBUTION**

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

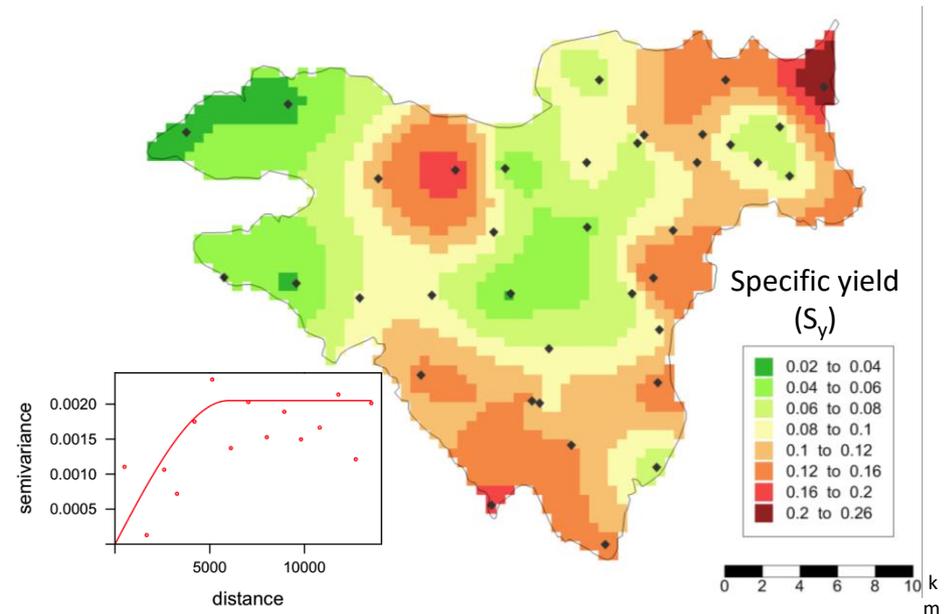
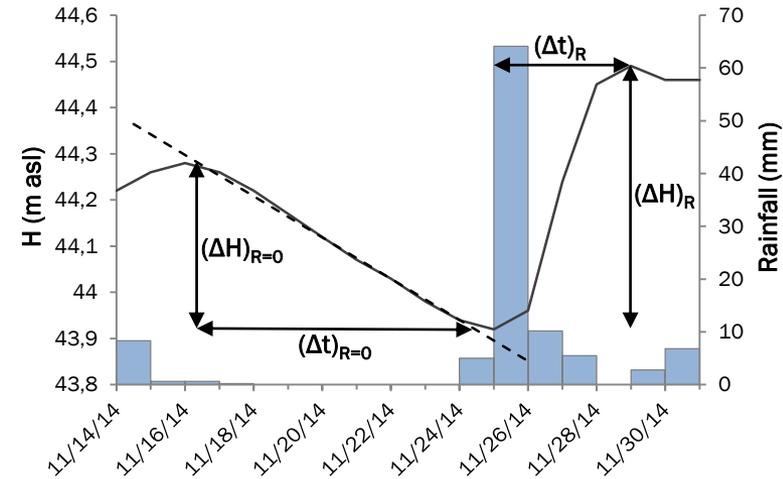
$$\left(\frac{\Delta H}{\Delta t}\right)_R S_y = P - (r + E + D)$$

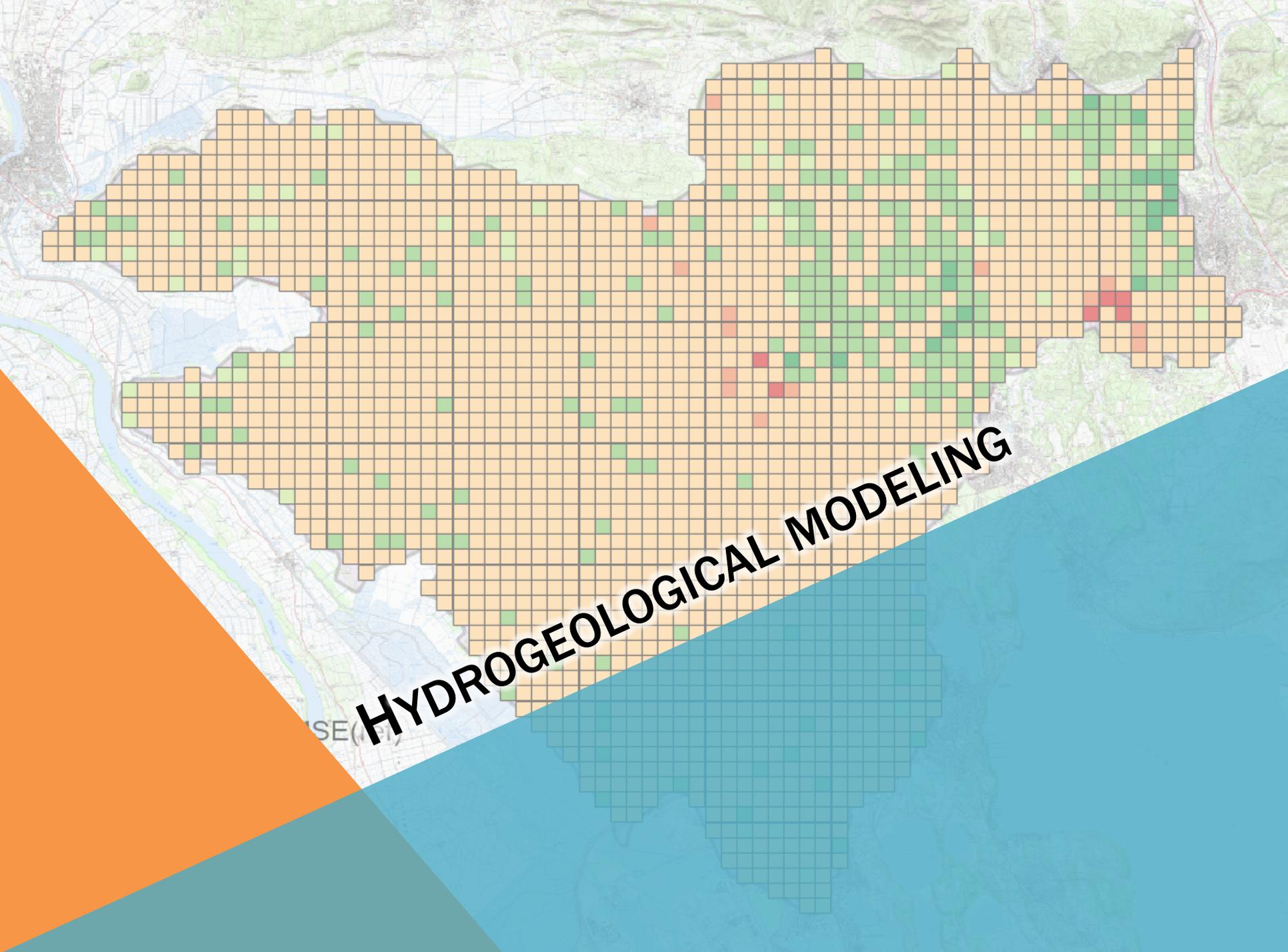
Assumptions:

- Negligible runoff over Crau aquifer:  $r \approx 0$
- Winter rainfall events:  $E \approx 0$
- 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

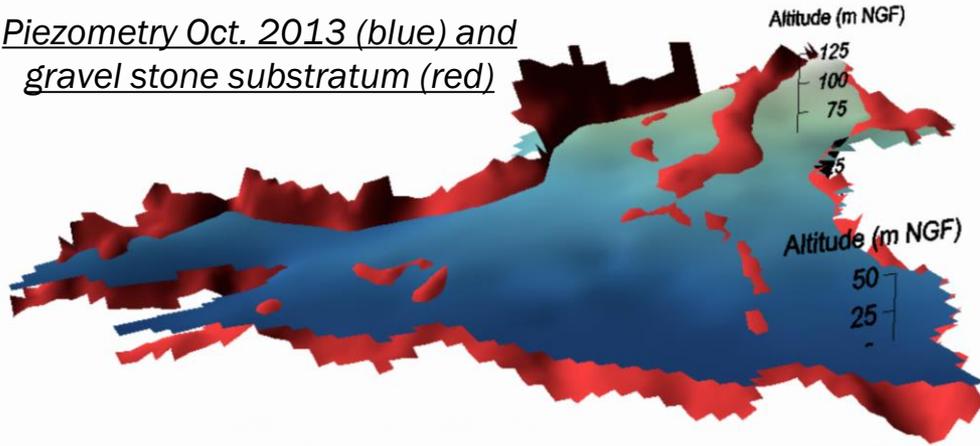


An aerial photograph of a city and surrounding areas, overlaid with a grid. The grid cells are colored in shades of orange, green, and red, representing different hydrogeological parameters. The grid covers a large area, including a river and urban areas. The text 'HYDROGEOLOGICAL MODELING' is written across the grid in a bold, black, sans-serif font, slanted upwards from left to right. The background is split into two diagonal sections: orange on the left and blue on the right.

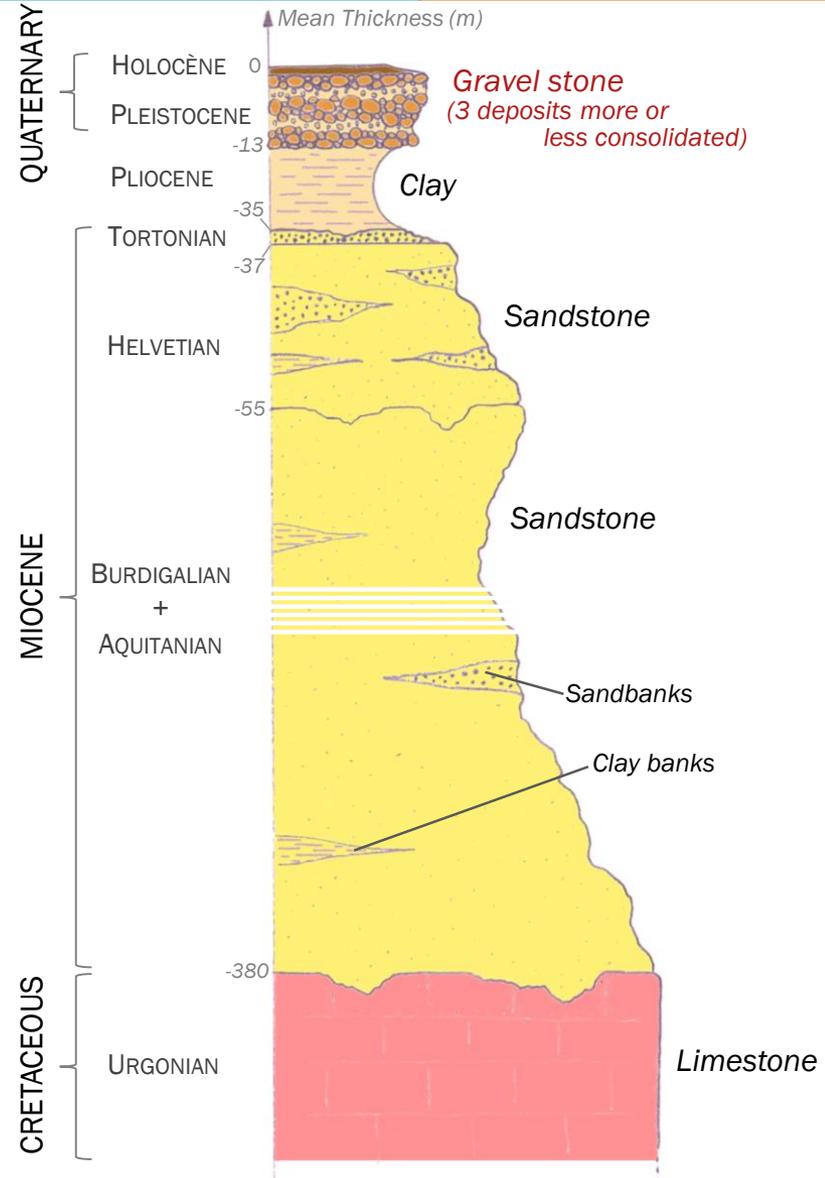
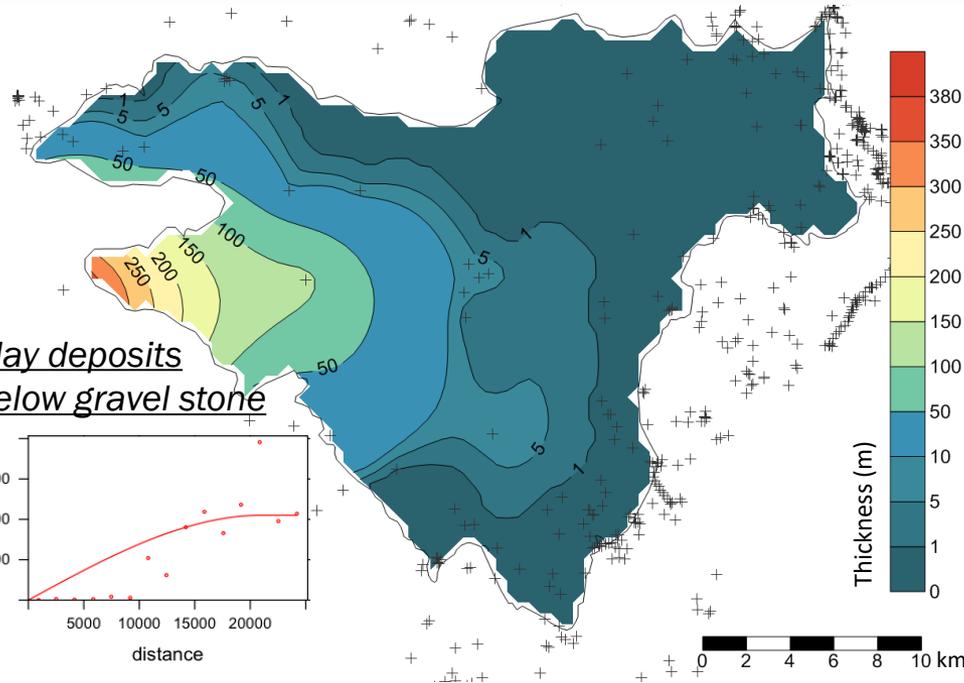
# HYDROGEOLOGICAL MODELING

# A NEW GEOLOGICAL MODEL

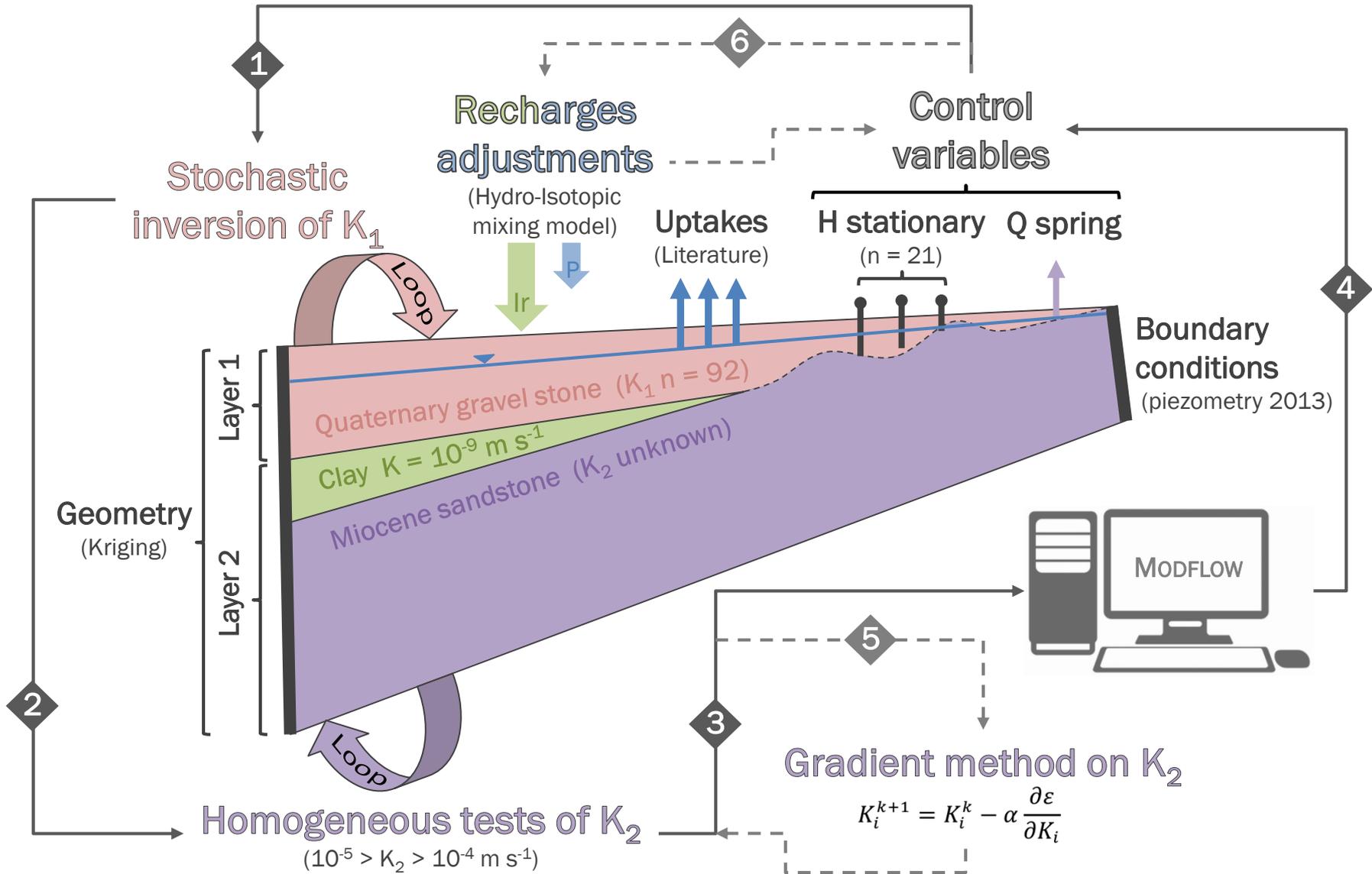
Piezometry Oct. 2013 (blue) and gravel stone substratum (red)



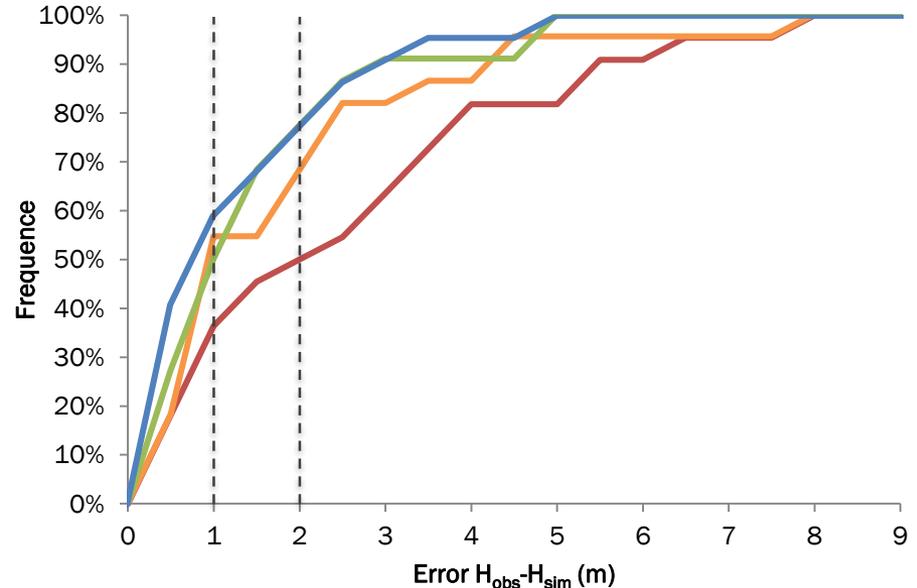
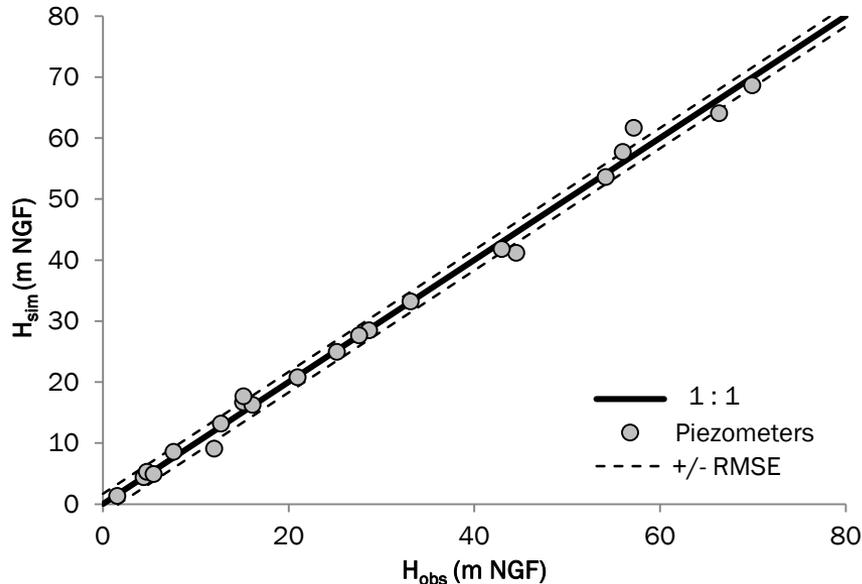
Clay deposits below gravel stone



# CALIBRATION OF THE STEADY STATE MODEL



- 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:  $R_n = 84 \text{ mm an}^{-1}$  et  $R_i = 1212 \text{ mm an}^{-1}$  (Blue)
  - Error = 1.15 m ; RMSE = 1.67 m



- Timing of seasonality

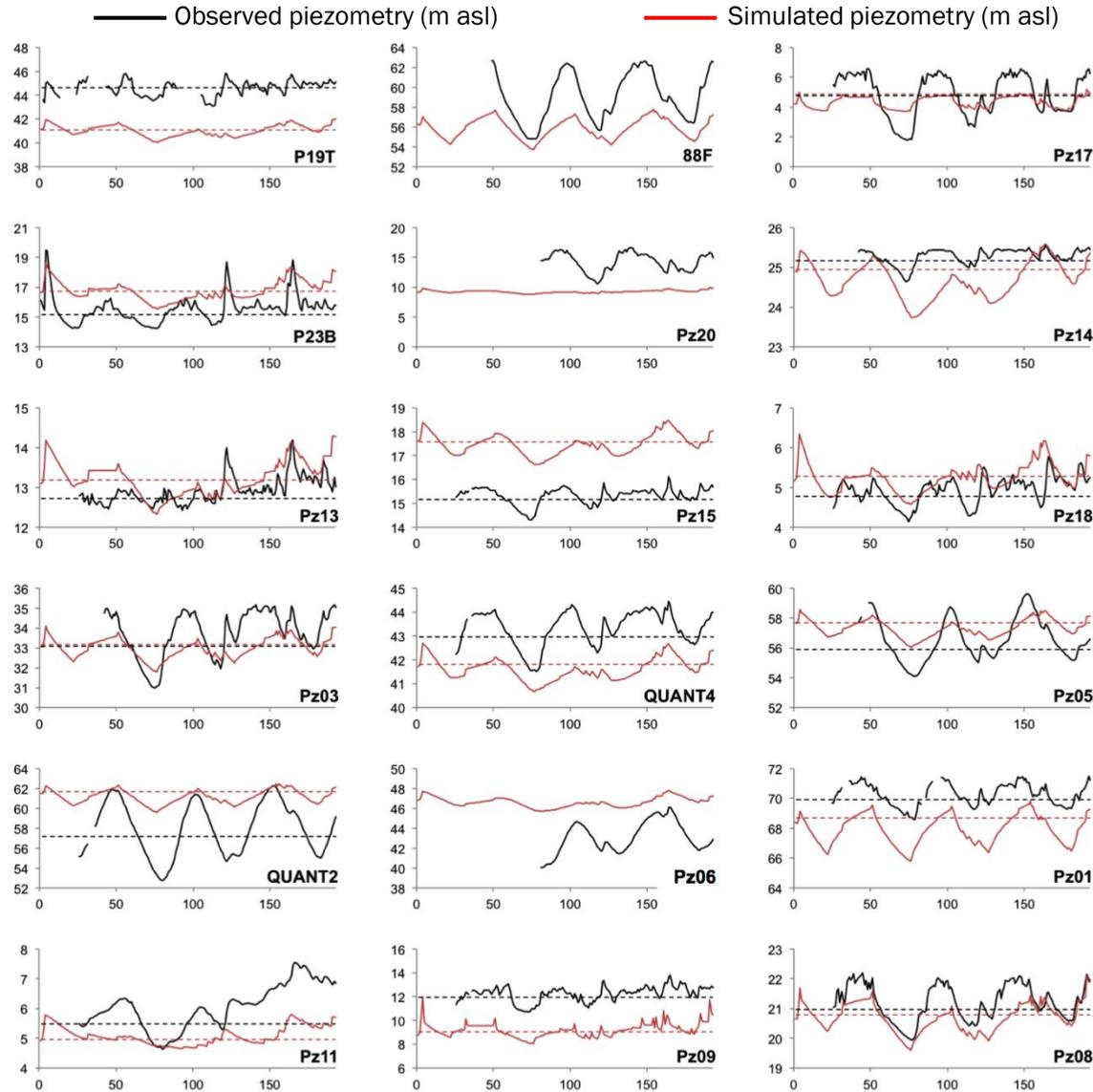
- Respecting irrigation periods and rainfall events

- Vertical offsets

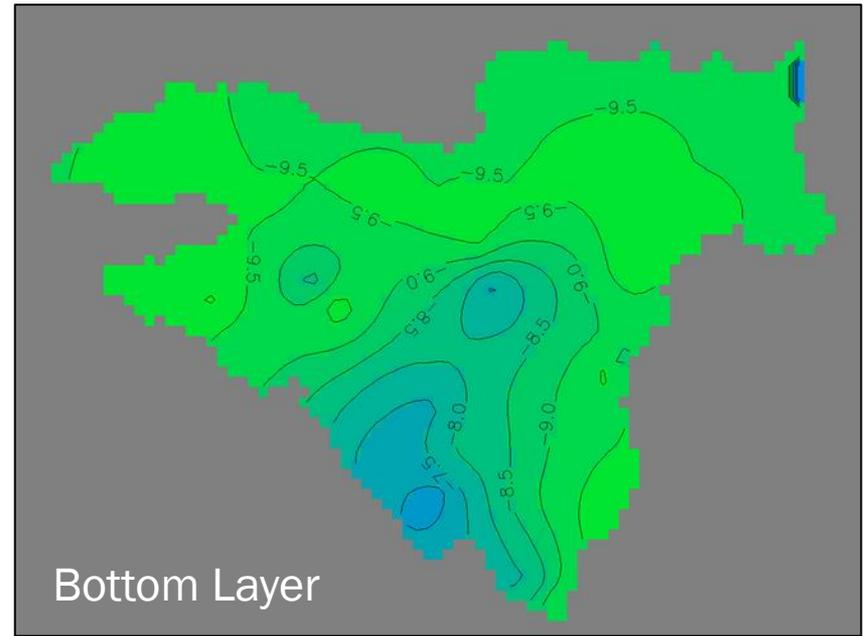
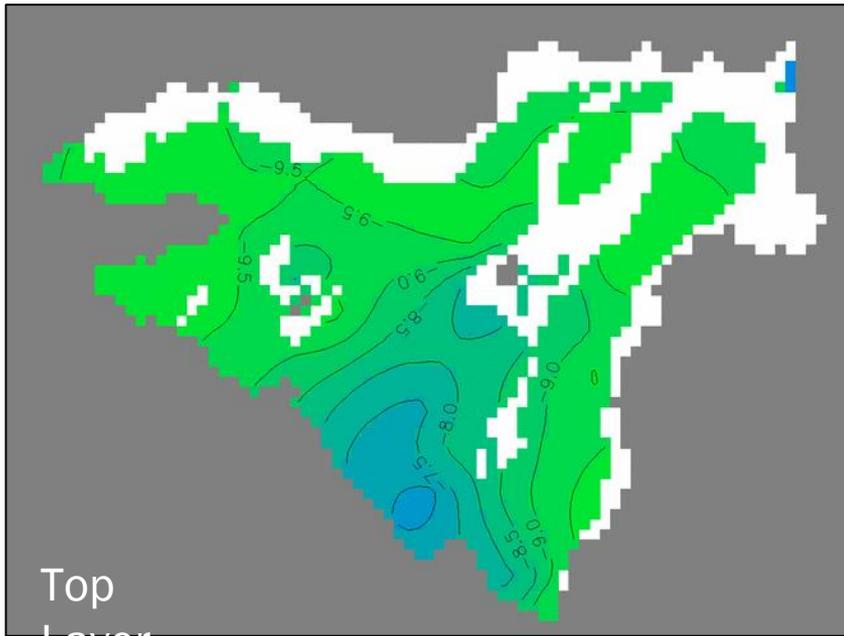
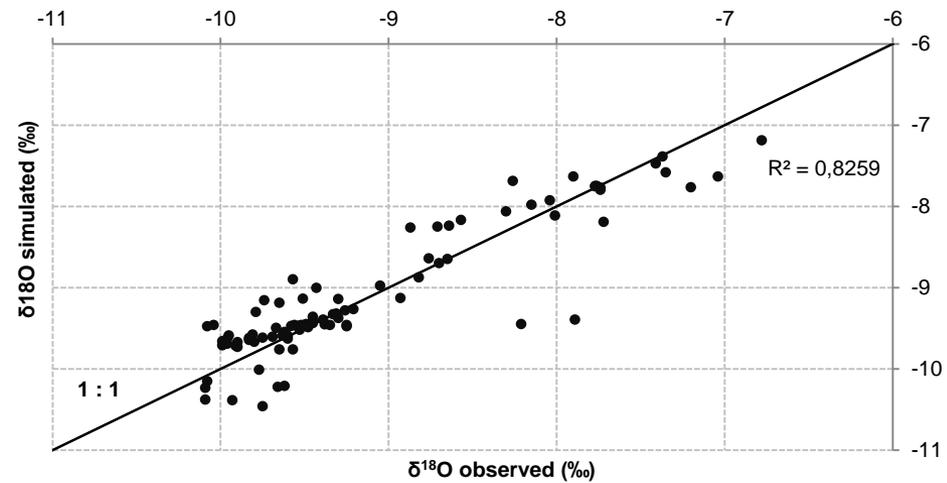
- Errors inherited from the steady-state model (dashed lines: red = simulated ; black observed)

- Amplitudes miss estimations

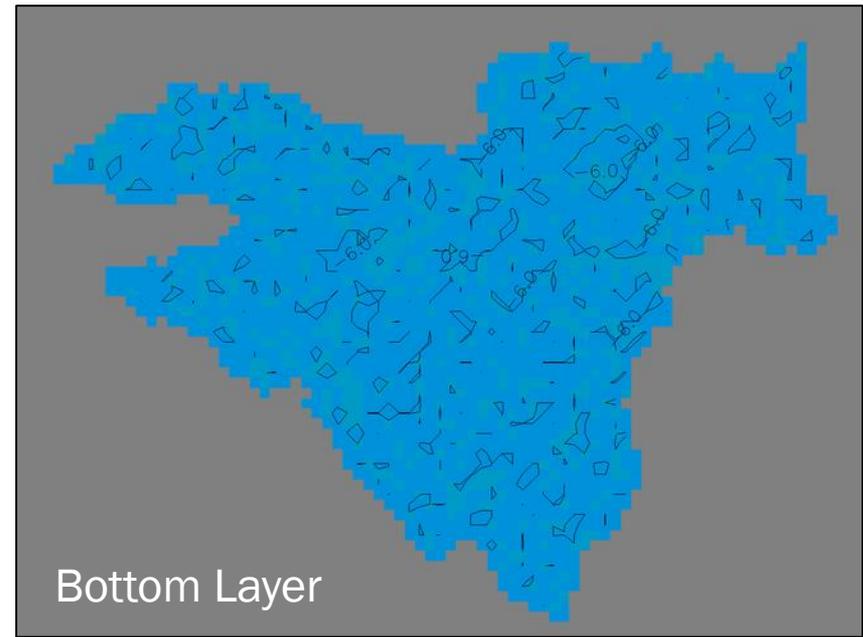
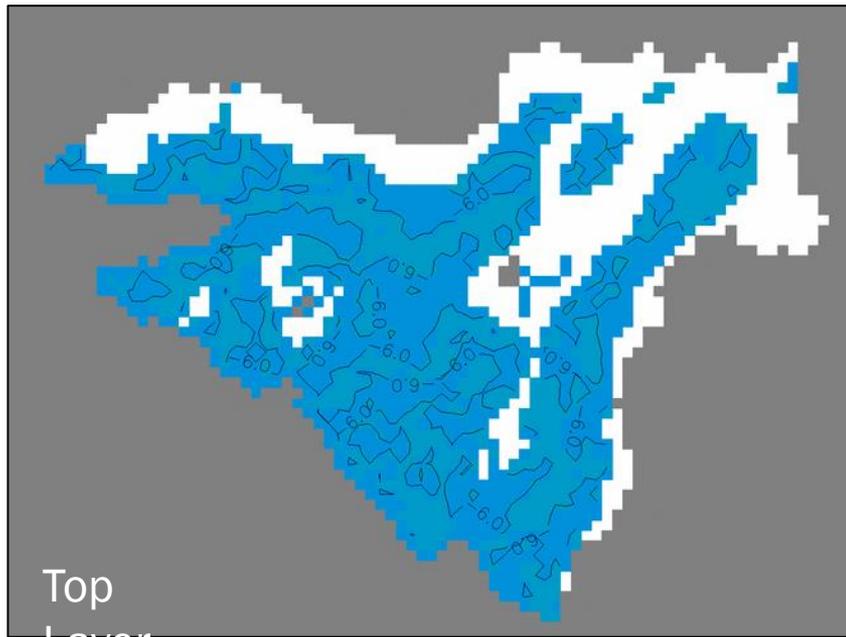
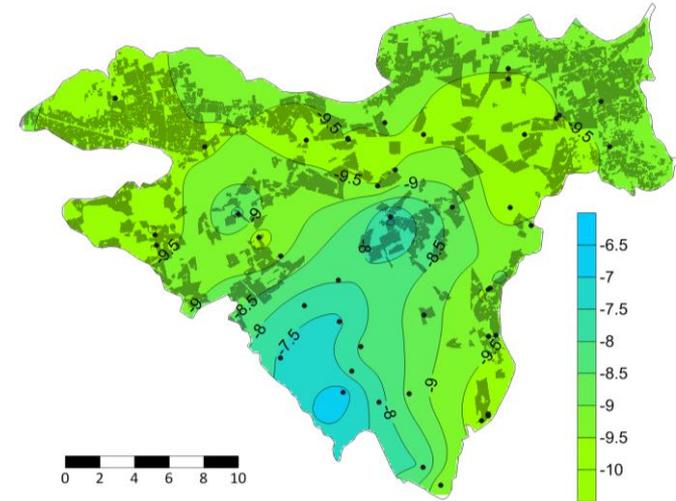
- Mainly caused by the use of a regional average value of the recharge by irrigation return flow (variable from one meadow to another)



- 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*

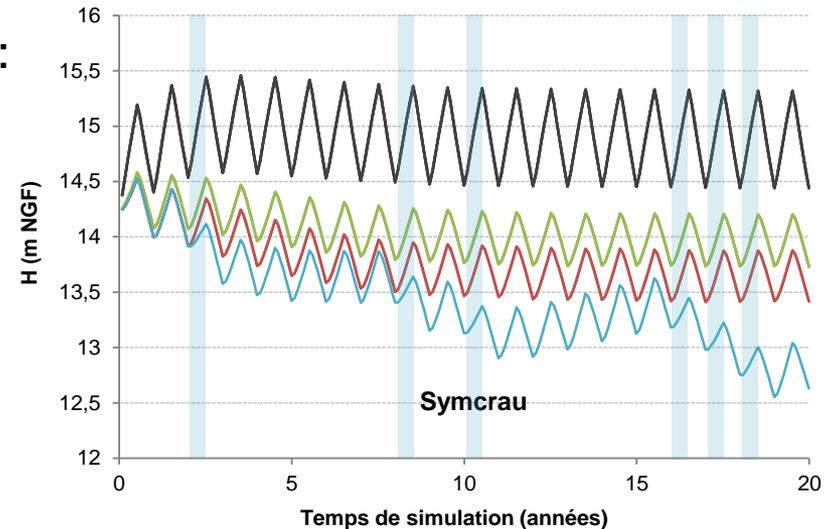


- 500 years of simulation, starting before the creation of irrigated meadows
  - Initial signal: natural recharge end-member (-6.00‰) for both layers
  - Uptakes only for the last century (Industrial revolution)
  - Meadows on the south-east part only for the last century



# IMPACTS AND CONCLUSIONS

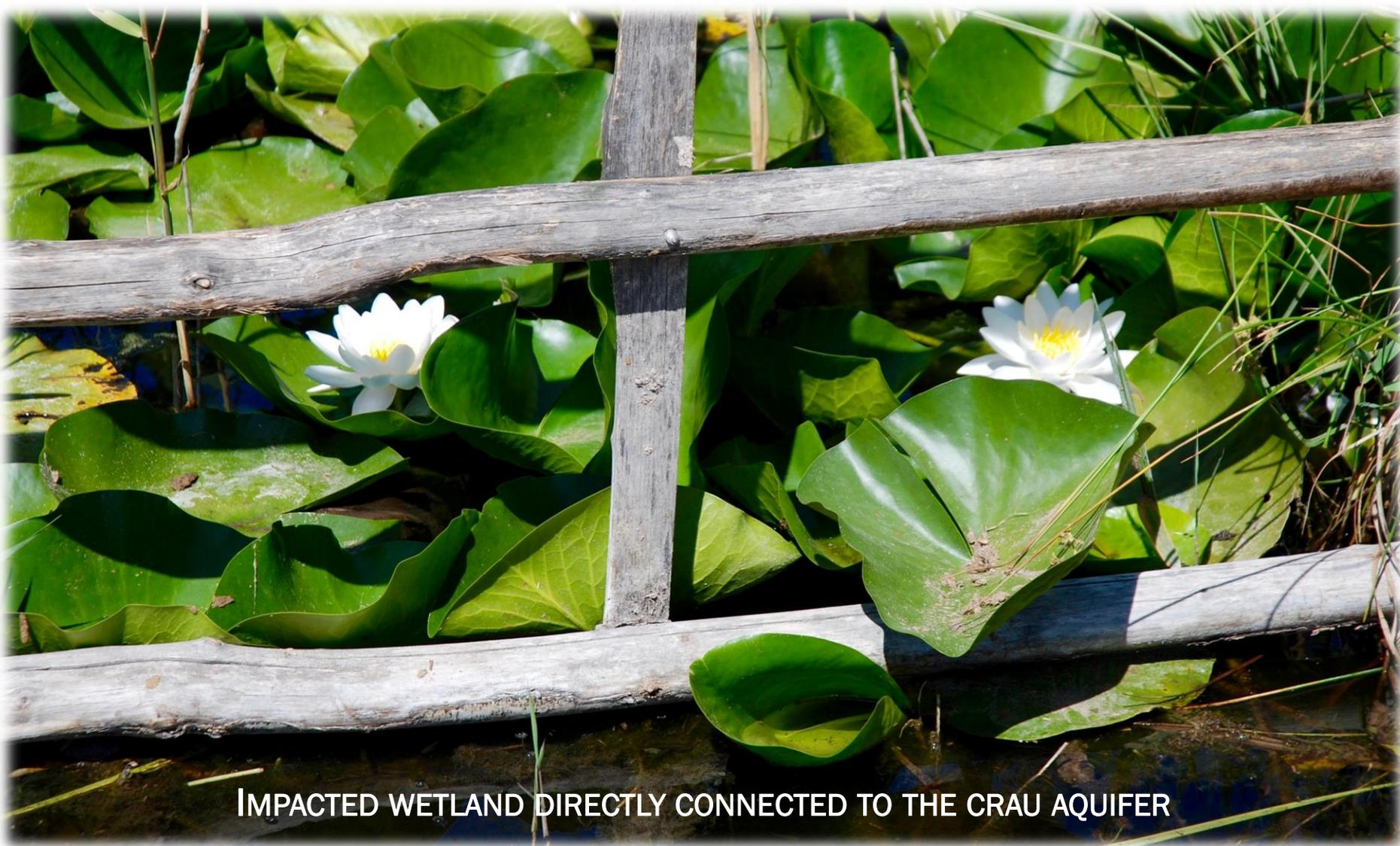
- Cumulated impacts of 2020-2040 scenarios :
  - Reference (Black)
  - Reduction of meadow surfaces by land-use planning:
    - -5 km<sup>2</sup> out of 140 km<sup>2</sup> (Green)
  - Global warming (IPCC AR5, 2014)
    - -8% of rainfall, RCP 8.5 (Red)
  - Simulation of water crisis:
    - -20% of irrigation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



IMPACTED WETLAND DIRECTLY CONNECTED TO THE CRAU AQUIFER

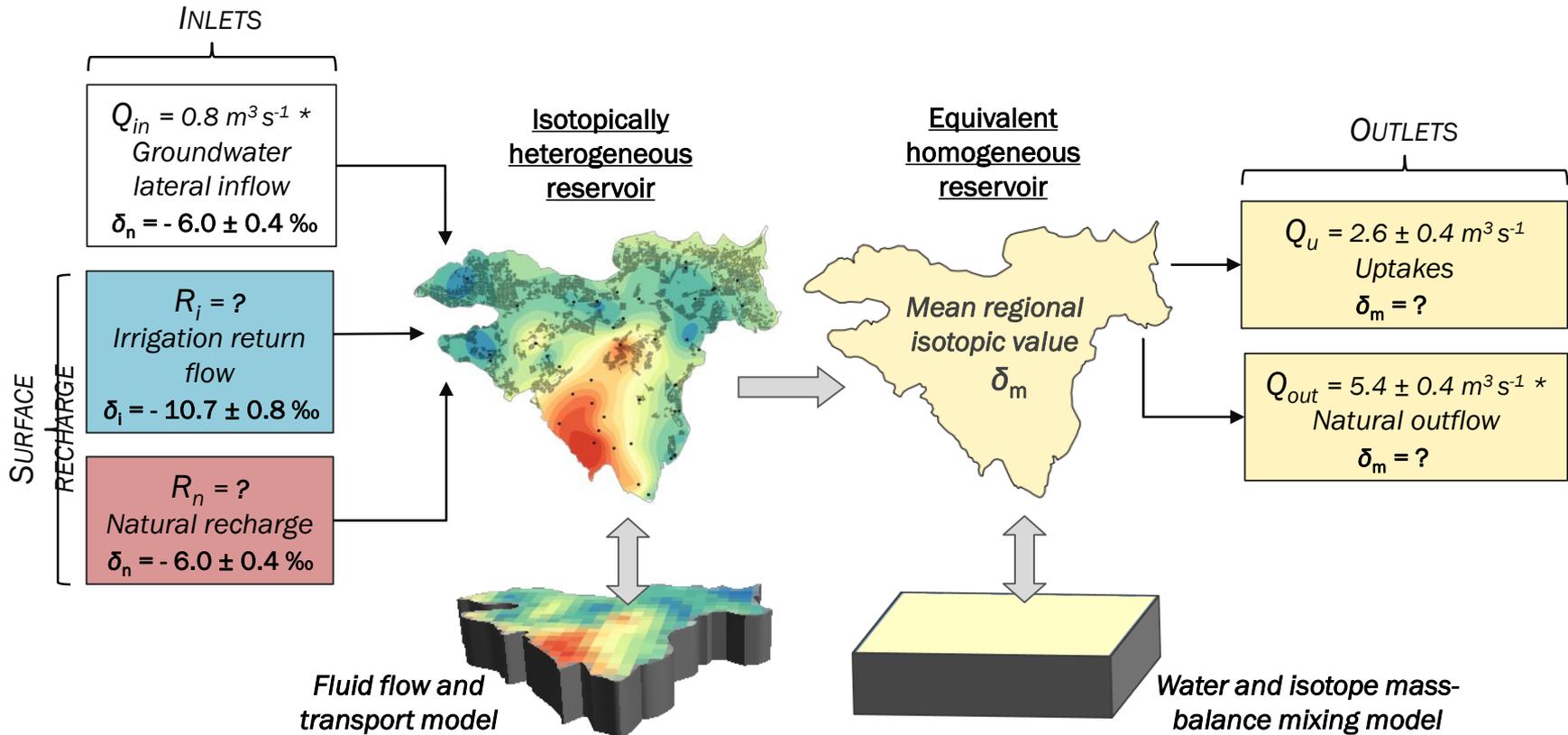
28/09/16

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43<sup>RD</sup>  
IAH CONGRESS



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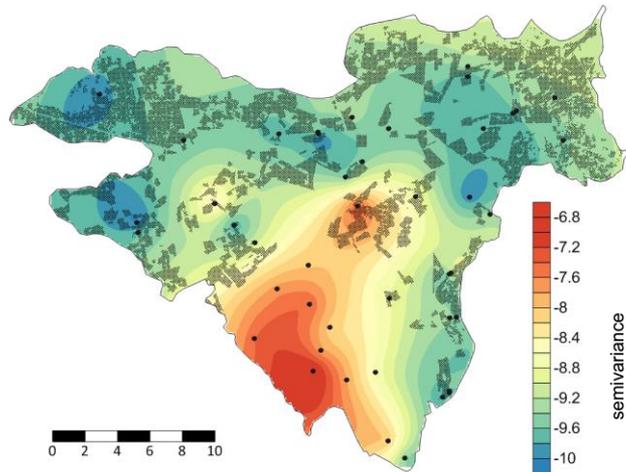
Water mass balance equation :

$$Q_u + Q_{out} = R_i + R_n + Q_{in}$$

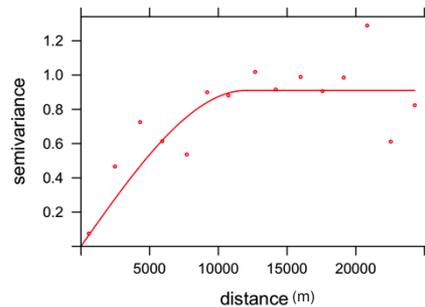
Hydro-isotopic mass balance equation :

$$\delta_m (Q_u + Q_{out}) = \delta_i R_i + \delta_n (R_n) + Q_{in}$$

# GEOSTATISTICAL APPROACH

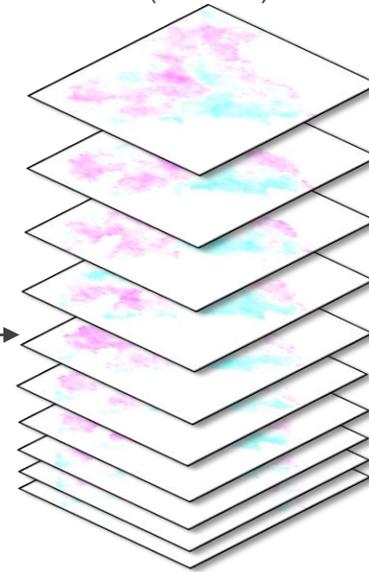


**Variogram of Spring 2012**  
**δ<sup>18</sup>O data**



## Sequential Gaussian Simulations (SGS)

(N = 100)



Mean  
and  
Standard  
deviation  
↑  
100 simulated  
values of δ<sub>m</sub>

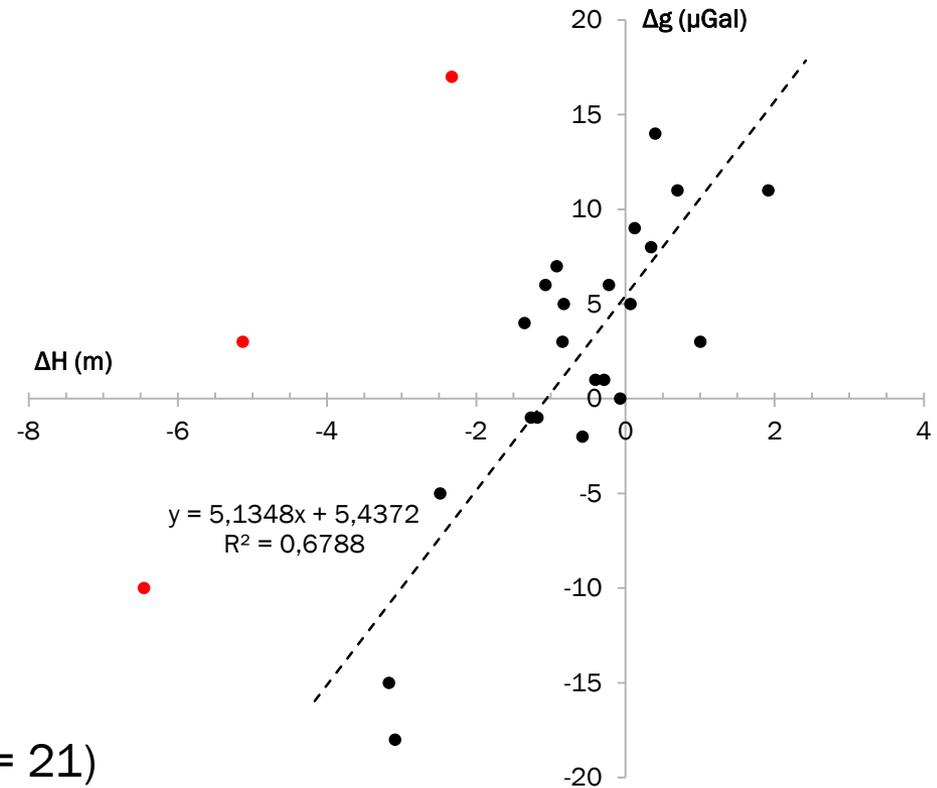
Irrigation return flow:  $R_i = \left( \frac{\delta_m - \delta_n}{\delta_i - \delta_n} \right) (Q_{out} + Q_u)$

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

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

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

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



- Regional specific yield =  $12.3 \pm 2\%$  (n = 21)
- Consistent with the WTF approach = 10.1% (n = 21)