Estimation of aquifer properties based on pressure variations at monitoring wells caused by transient water-supply pumping

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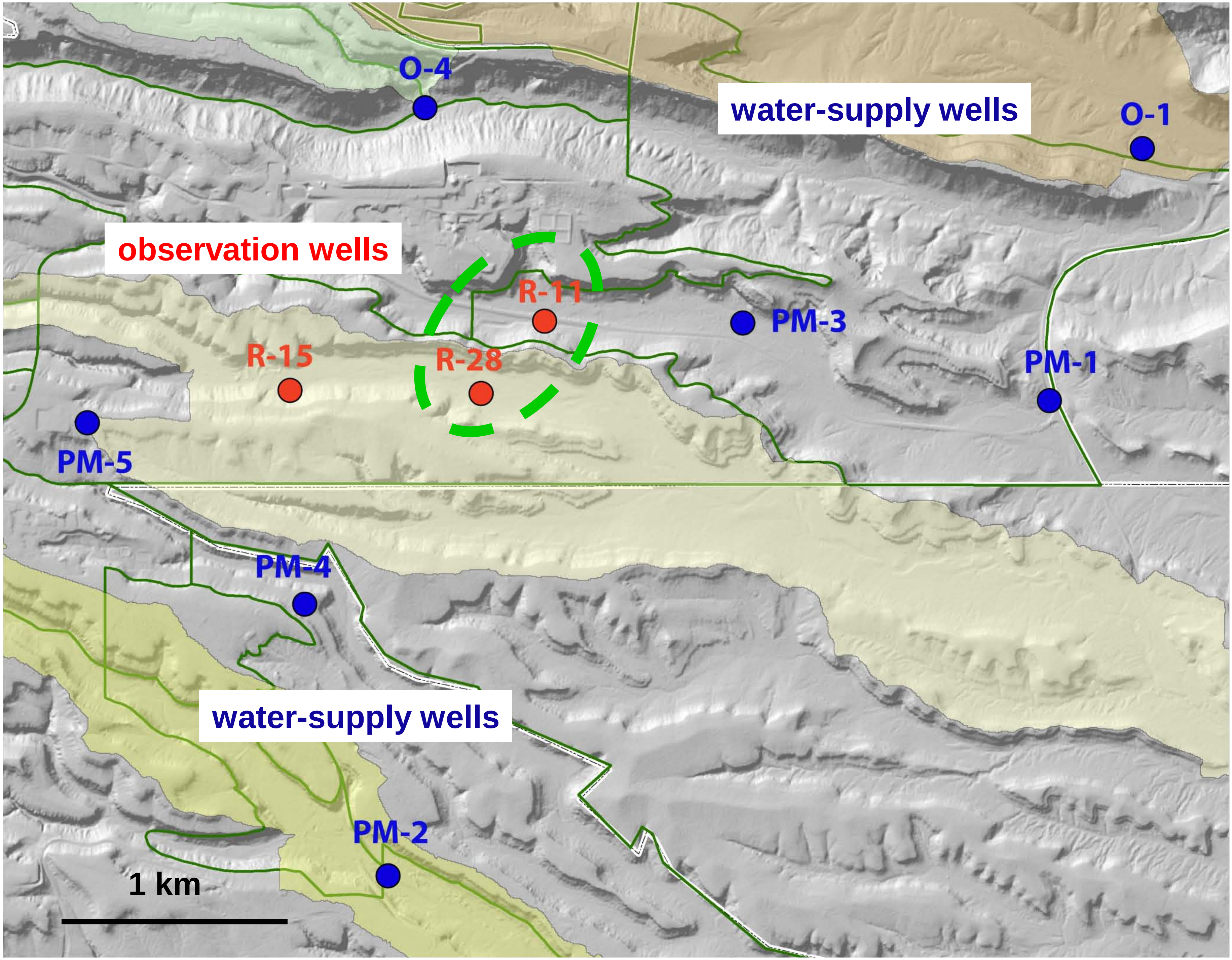
Problem statement

- Characterization of large-scale variability of aquifer properties (aquifer heterogeneity) is a difficult but very important task (e.g. for model predictions of contaminant transport)
- Standard (single/cross-well) pumping tests are applied usually. However, the tests may be expensive and difficult to execute (e.g. may require substantial time for aquifer recovery before pumping test; measurement errors may be substantial when drawdowns are small)
- Analyzing aquifer responses at monitoring wells to pumping transients that occur naturally during water-supply pumping may be a much cheaper and better alternative. In this case, data are collected at multiple pumping and observation wells
- Some of the benefits in analyzing responses to water-supply pumping transients when compared to standard pumping tests are:
  - Cheap
  - Aquifer is stressed more intensely
  - Long-term records (+ repetitions in pumping regimes) allow reduction of measurement errors and estimation uncertainties
  - Multiple stress points (pumping wells) and observation points (monitoring wells) allow for an efficient tomographic analysis (Neuman, 1972; Vesselinov et al., 2001; etc) of aquifer heterogeneity

Study area

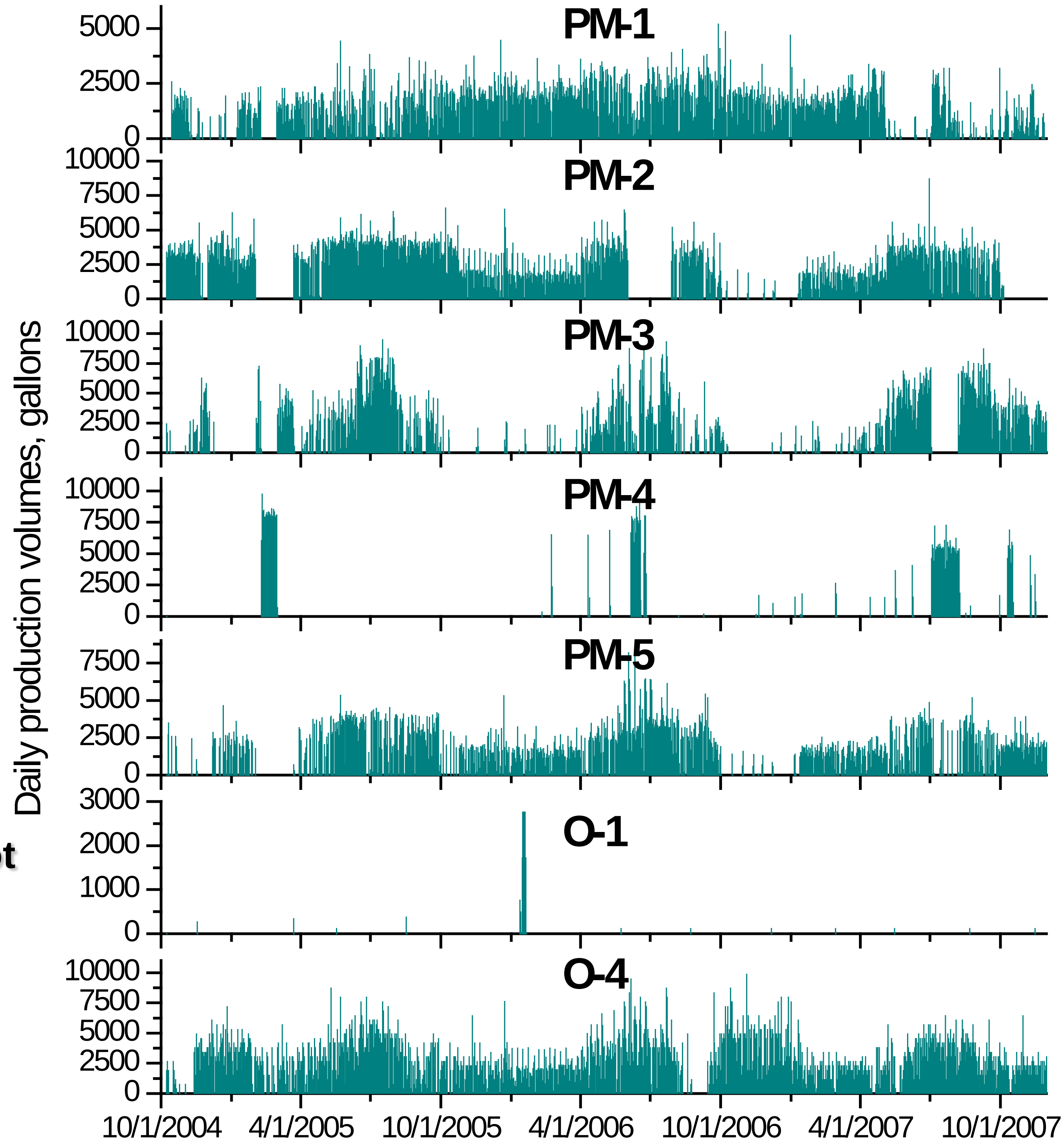
- Regional aquifer beneath Los Alamos National Lab (LANL), Northern New Mexico, USA
- Aquifer is highly heterogeneous; complex 3D flow conditions
- 7 water-supply wells in close vicinity to the study area; more (~20) water-supply wells close by
- ~50 observation wells
- ~100 well screens
- 3,309,682 water-level observations (currently)
- 70,248 daily pumping records (currently)
- Contaminants derived from LANL are observed in the regional aquifer



O-4
water-supply wells
O-1
observation wells
R-11
PM-3
R-15
R-28
PM-1
PM-5
PM-4
water-supply wells
PM-2
1 km

Pumping records (10/2004-12/2007)

- ❖ ~3-year record
- ❖ Daily data
- ❖ Unique patterns
- ❖ PM-2, PM-5, and O-4 are the major water producers (note the different scales of y-axes)
- ❖ New data already available but have not been analyzed yet



Water-level records (span ~3 years)

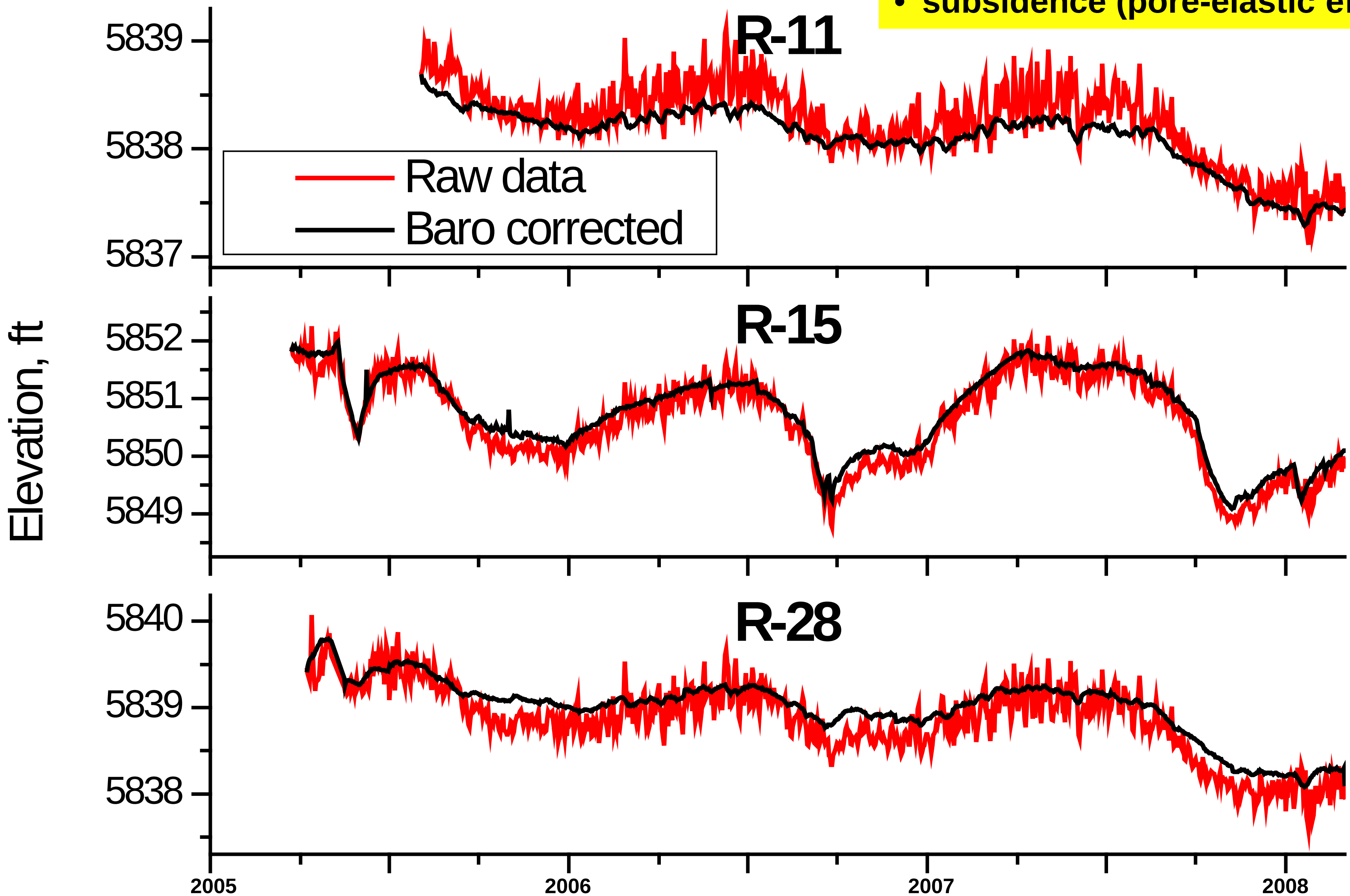
~15 min-1h temporal resolution

~3 ft (1 m) fluctuations at R-15

~1 ft (0.3 m) fluctuations at R-11 and R-28; fluctuations at R-11 and R-28 are similar

Potential transient influences:

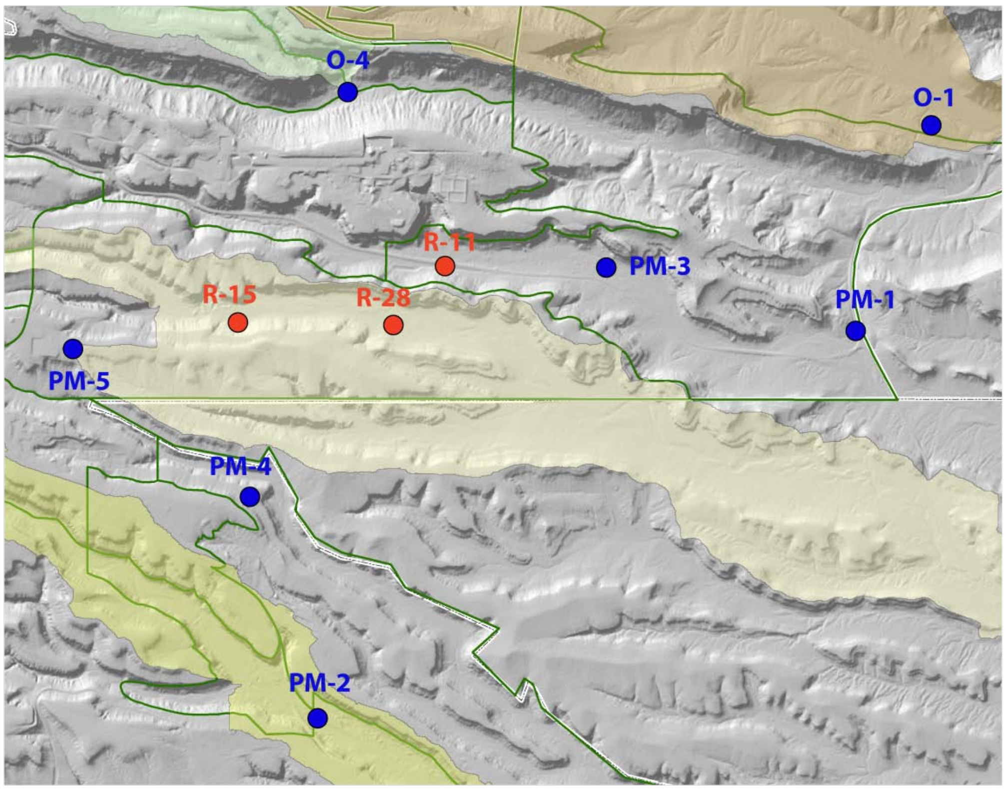
- **pumping effects**
- **barometric effects**
- **variability in the ambient flux**
- **variability in local recharge**
- **subsidence (pore-elastic effects)**

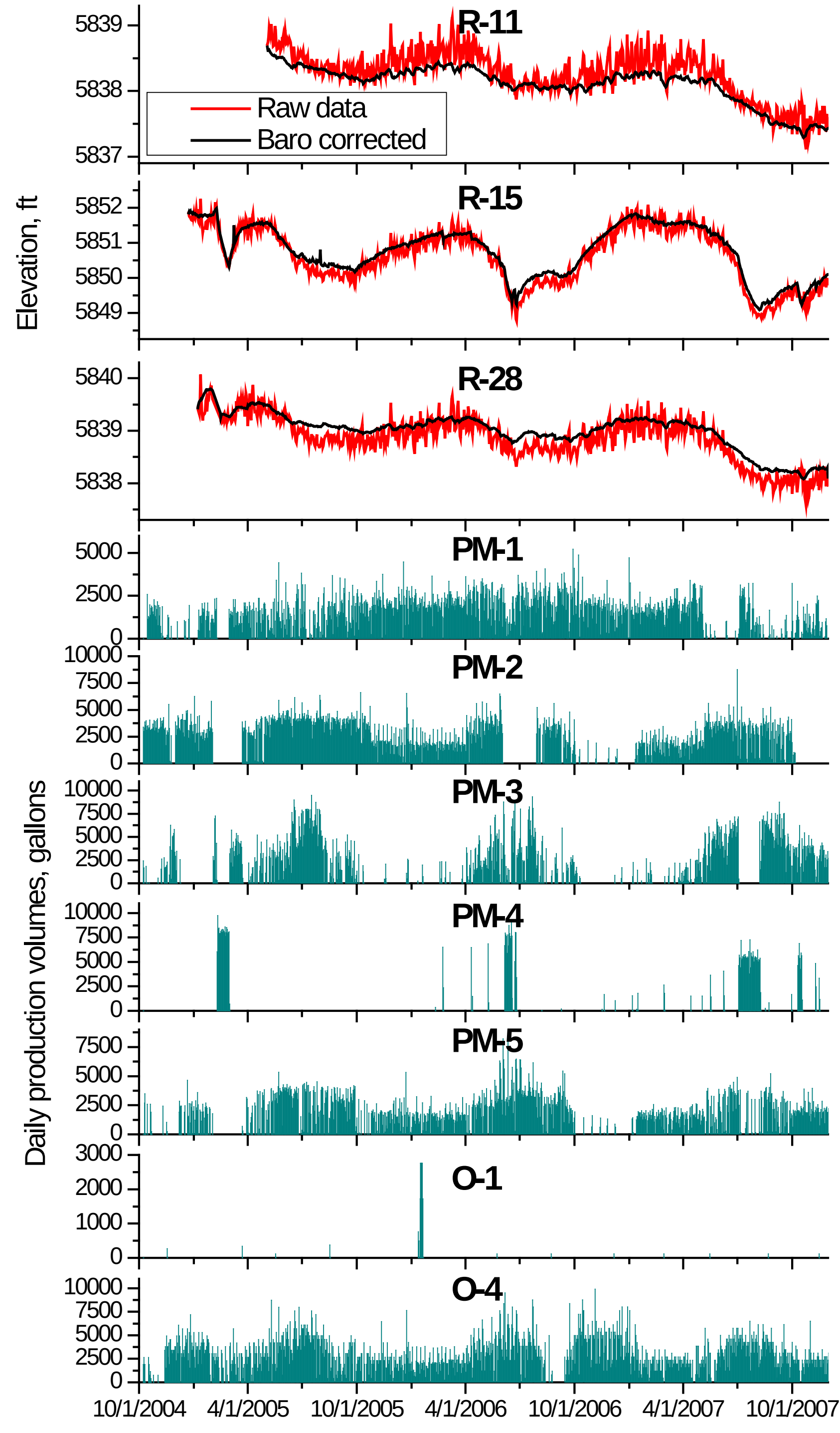


Water-level vs. pumping records

Visual comparisons demonstrate correlations between the water levels and the pumping regimes. Goals:

1. **Fingerprint the pumping wells causing the observed water-level fluctuations**
2. **Estimate effective aquifer properties using a simple analytical method**
3. **Estimate aquifer heterogeneity using a tomographic approach based on a simple numerical model**





Methodology of Approach 1: Analytical analysis

- Simple analytical model (Theis + superposition) taking into account the pumping records of all the pumping wells (7)
- Pressure variations of each monitoring well (R-11, R-15, R-28) are analyzed independently
- Calibration of the analytical model to reproduce observed pressures variations using Levenberg-Marquardt algorithm
- As a result, effective large-scale properties (T & S) of the aquifer between pumping and monitoring wells are estimated
- The same results could have been obtained if specially designated pumping tests were conducted at each water-supply wells
- The numerical models are created and the obtained results are analyzed using automated (interactive) pre- and post-processing. In this way, the models can easily be updated when new data become available
    - Model-input files are automatically generated
    - All the information (water levels, pumping records, well locations, etc) is automatically extracted from a database and applied in the inverse models

Theis equation

$$s = \frac{Q}{4\pi T} W(u) = \frac{Q}{4\pi T} W\left(\frac{r^2 S}{4Tt}\right)$$

s - drawdown (L), Q - pumping rate (L^3T^{-1}), T - transmissivity (L^2T^{-1}), $W(u)$ - well function r - distance between the pumping well and observation well (L), S – storativity, t - time since pumping commenced (T).

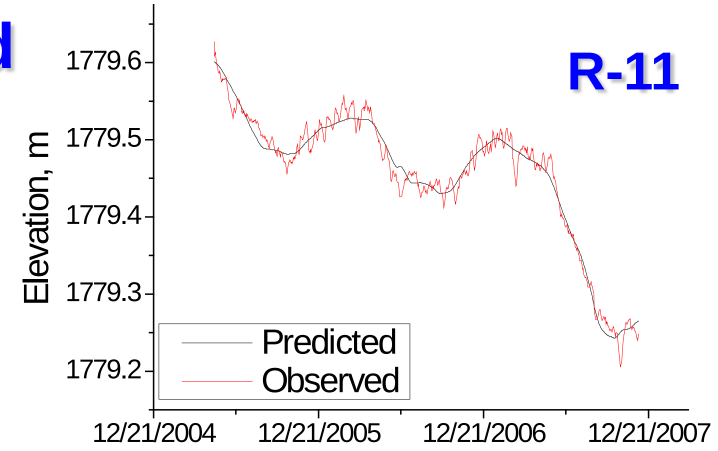
Theis equation applying the principle of superposition

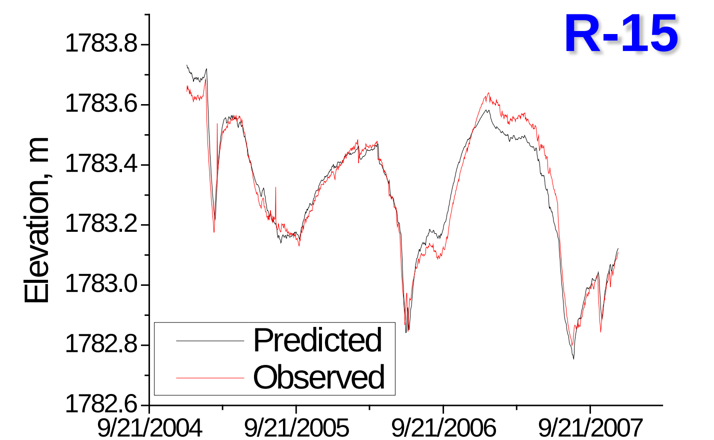
$$s = \sum_{i=1}^{N} \sum_{j=1}^{M_i} \frac{Q_{ij} - Q_{ij-1}}{4\pi T_i} W\left(\frac{r_i^2 S_i}{4T_i\left(t - t_{Qij}\right)}\right)$$

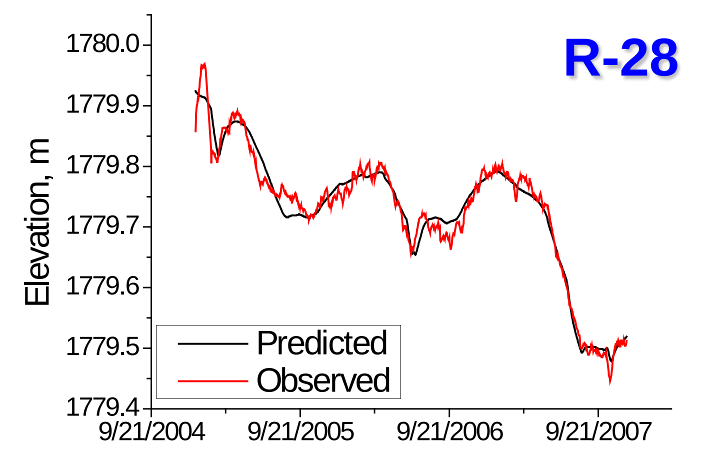
N - number of pumping wells, M_i - number of pumping periods (i.e. number of pumping rate changes), Q_{ij} - pumping rate of well i during pumping period j, and t_{Qij} - time when the pumping rate changed at well i during pumping period j

Inverse results using analytical method

- **>1,000 calibration targets**
- **15 adjustable aquifer parameters in each inverse model: 7 effective T's; 7 effective S's; initial water level**
- **<u>The model fingerprints the pumping wells that produce the observed drawdown responses</u>**
- **Pumping wells that do not produce drawdown responses are rejected in the model by estimating effective properties that preclude pumping drawdowns (e.g. high T; low S)**

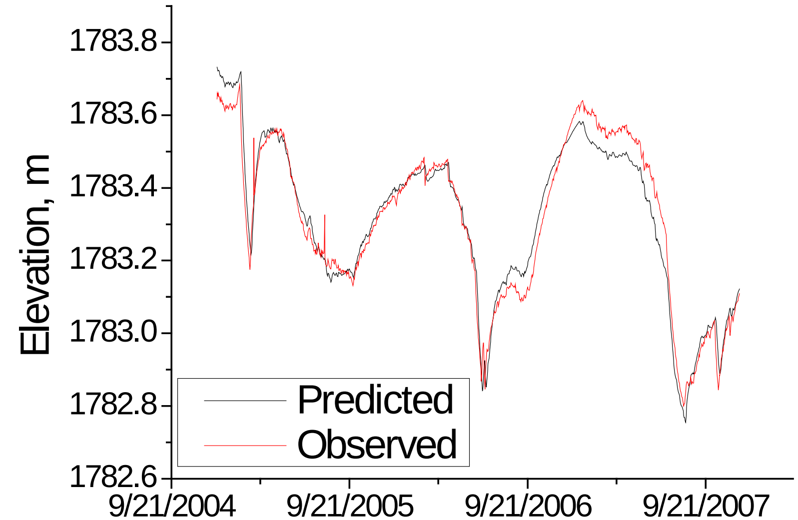


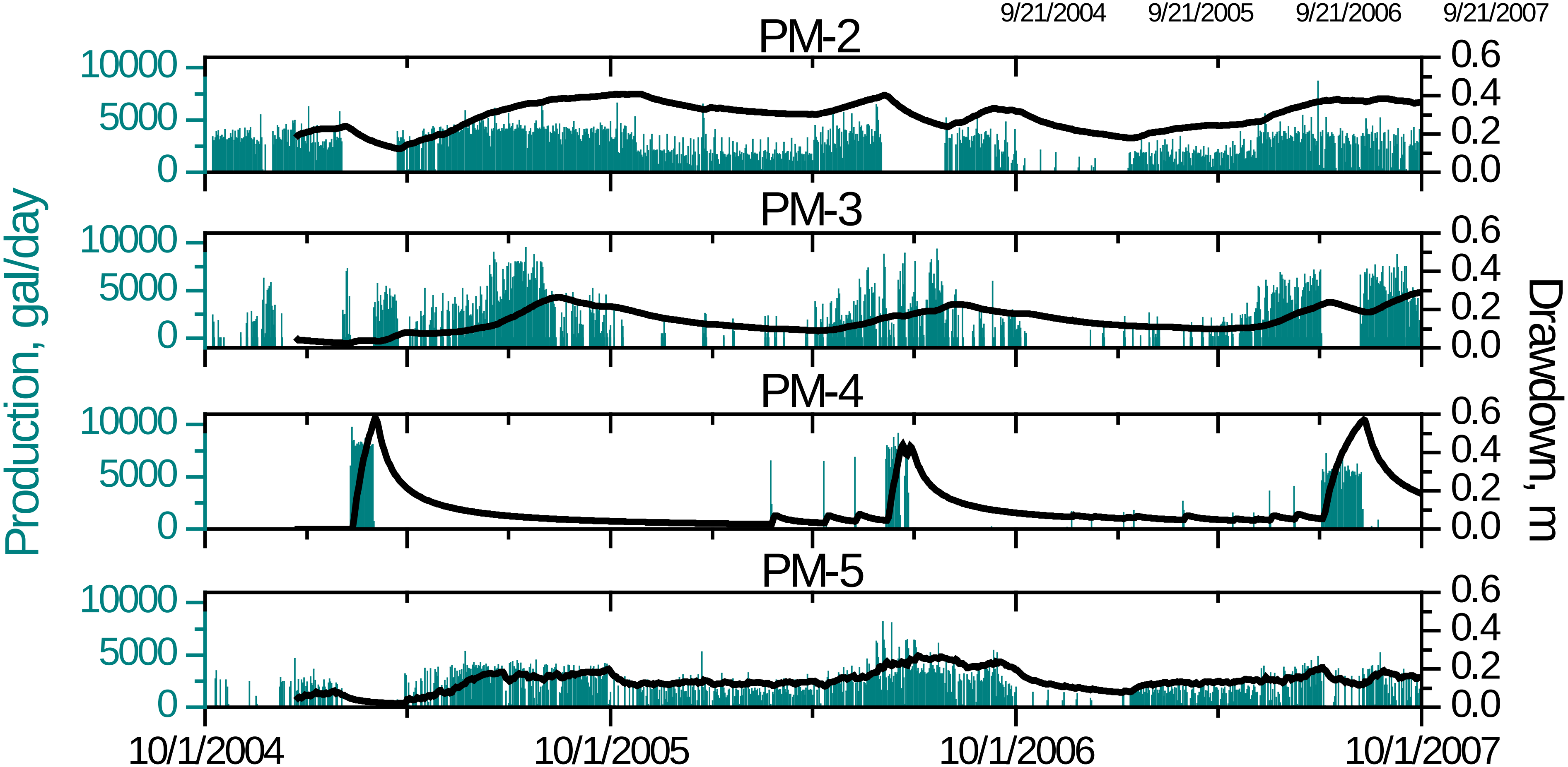




Deconstruction of R-15 transients

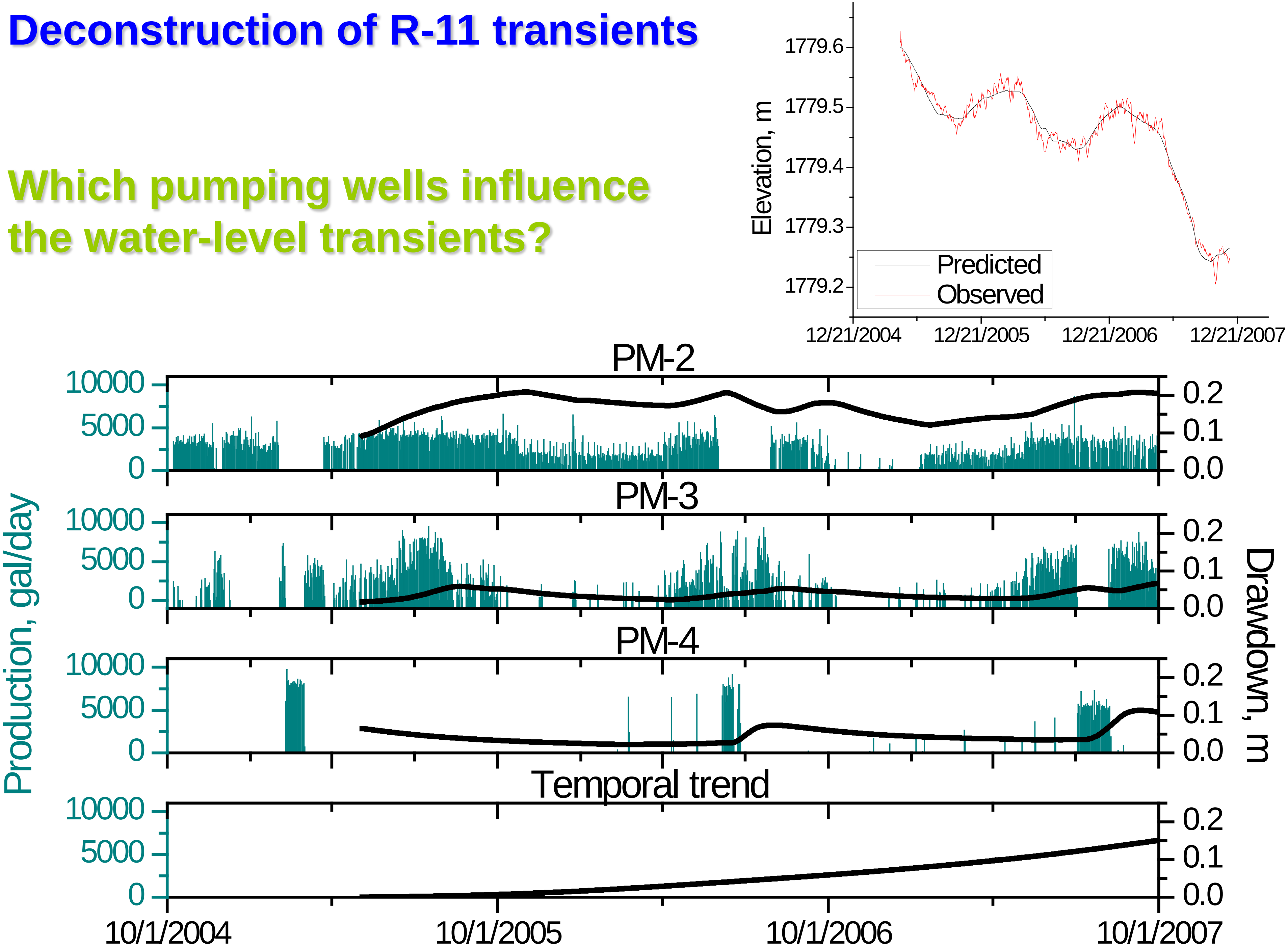
Which pumping wells influence the water-level transients?





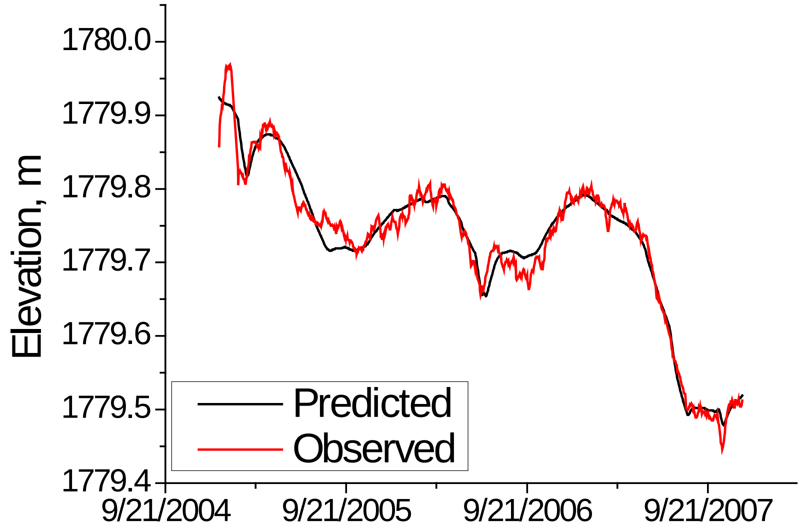
Deconstruction of R-11 transients

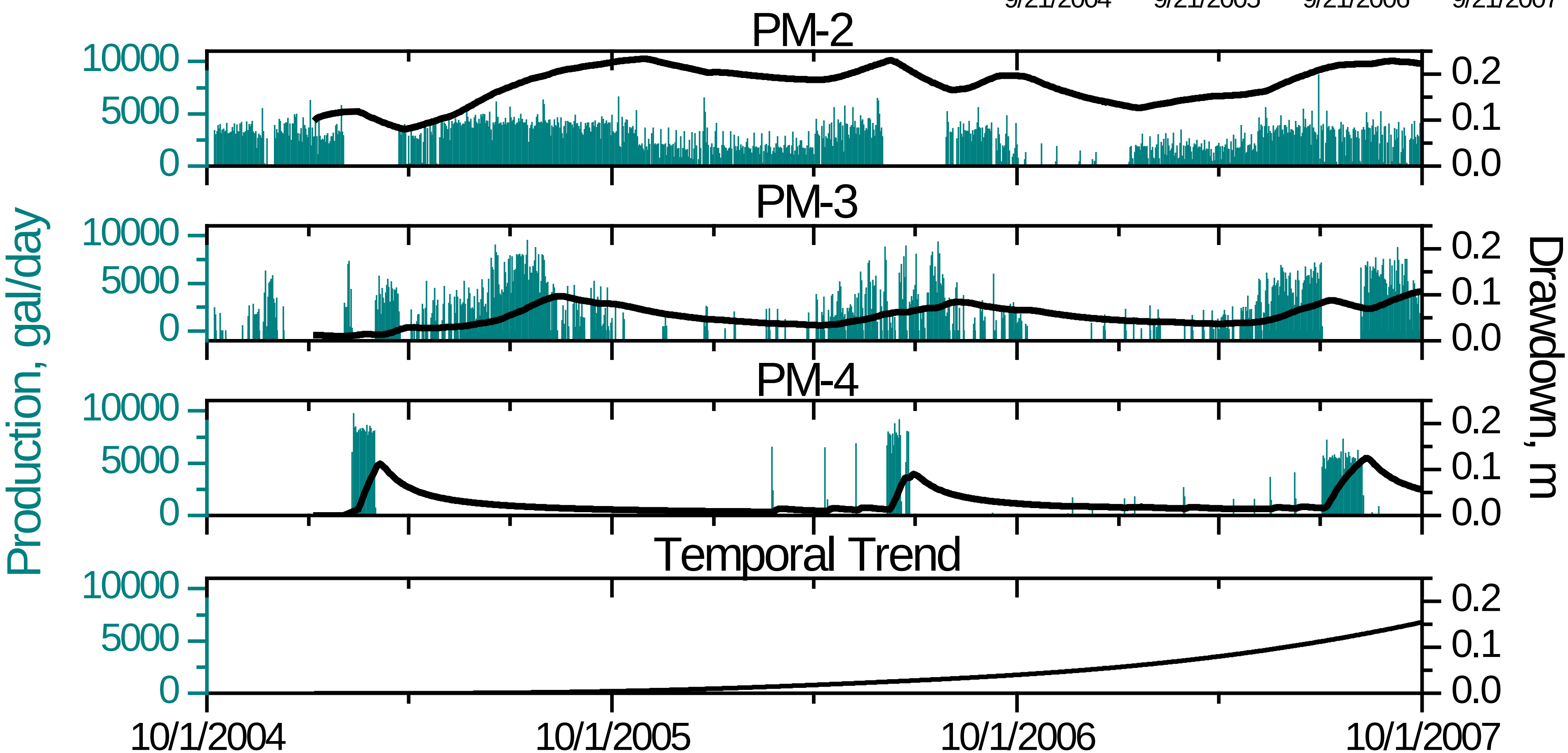
Which pumping wells influence the water-level transients?

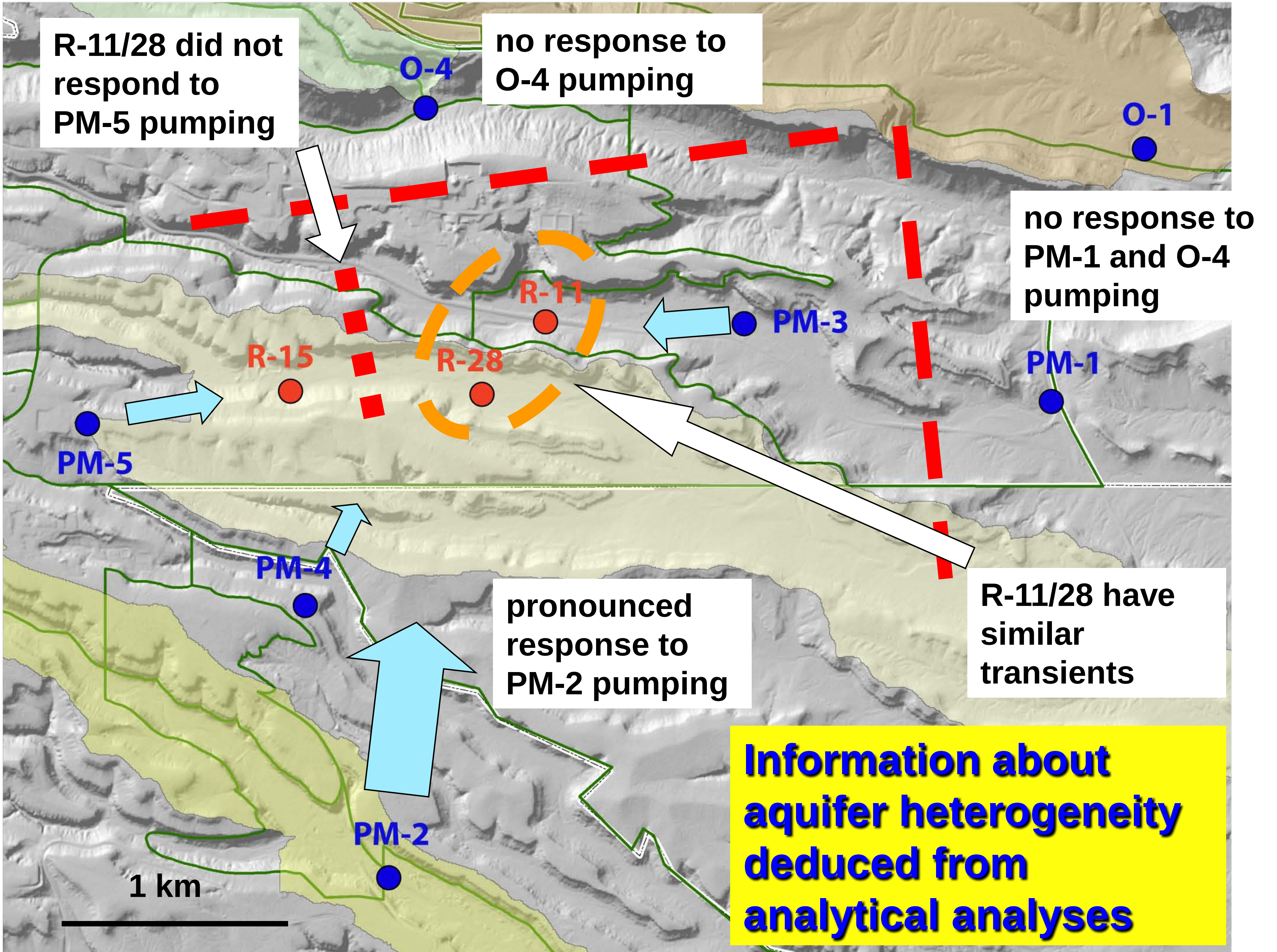


Deconstruction of R-28 transients

Which pumping wells influence the water-level transients?






R-11/28 did not respond to PM-5 pumping
no response to O-4 pumping
O-4
O-1
no response to PM-1 and O-4 pumping
R-11
PM-3
R-15
R-28
PM-1
PM-5
R-11/28 have similar transients
PM-4
pronounced response to PM-2 pumping
Information about aquifer heterogeneity deduced from analytical analyses
PM-2
1 km

Inverse results using analytical method

Effective parameter estimates; if standard cross-hole pumping tests have been conducted at each water-supply well, similar parameter estimates would have been obtained

$\log_{10} T$ [m^2/d]

	PM-1	PM-2	PM-3	PM-4	PM-5	O-1	O-4
R-11	-	3.5	4.0	3.2	-	-	-
R-15	-	3.3	3.4	3.2	3.7	-	-
R-28	-	3.5	3.8	3.7	-	-	-
						Mean	3.5
						Variance	0.069

$\log_{10} S$ [-]

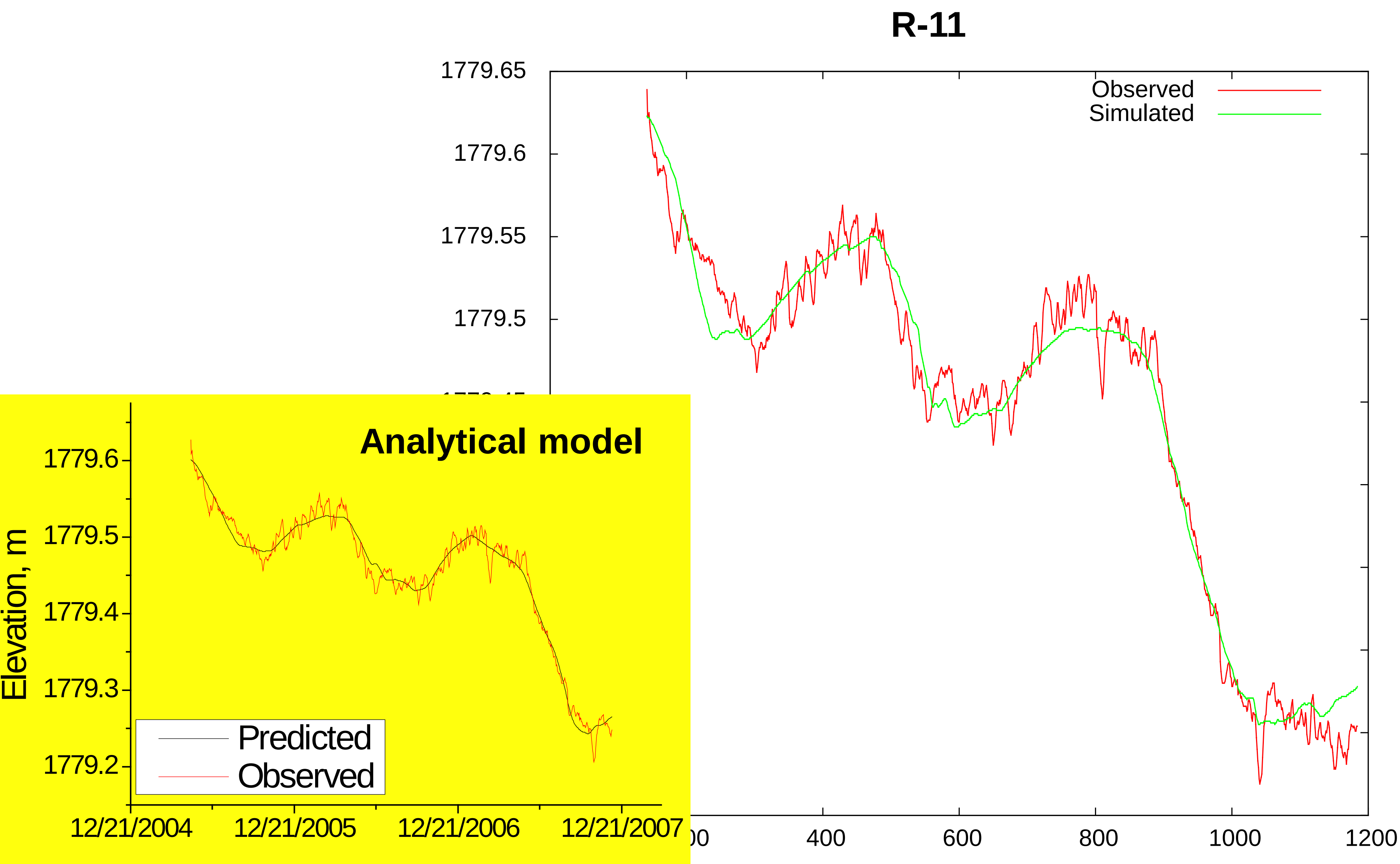
	PM-1	PM-2	PM-3	PM-4	PM-5	O-1	O-4
R-11	-	-1.5	-0.1	-1.1	-	-	-
R-15	-	-1.9	-1.5	-1.7	-1.5	-	-
R-28	-	-1.5	-0.4	-1.2	-	-	-
						Mean	-1.2
						Variance	0.4

Methodology of Approach 2: Hydraulic Tomography

- **Simple numerical model (2D, transient) taking into account the pumping records of all the pumping wells**
- **Calibration of the numerical model to reproduce observed pressures variations using Levenberg-Marquardt algorithm**
- **Pressure records of all the monitoring well (currently, R-11, R-15, R-28) are simultaneously analyzed**
- **Spatial heterogeneity of the aquifer is estimated using a geostatistical method (kriging and pilot points [de Marsily, 1976])**
- **The numerical models are created and the obtained results are analyzed using automated (interactive) pre- and post-processing. In this way, the models can easily be updated when new data become available**
  - **Computational grids and input files are automatically generated**
  - **All the information (water levels, pumping records, well locations, etc) is automatically extracted from a database and applied in the inverse models**

Inverse results using numerical model

How accurately can the numerical model reproduce observed water-levels based on the pumping records of all the water-supply wells?



Inverse results using numerical model

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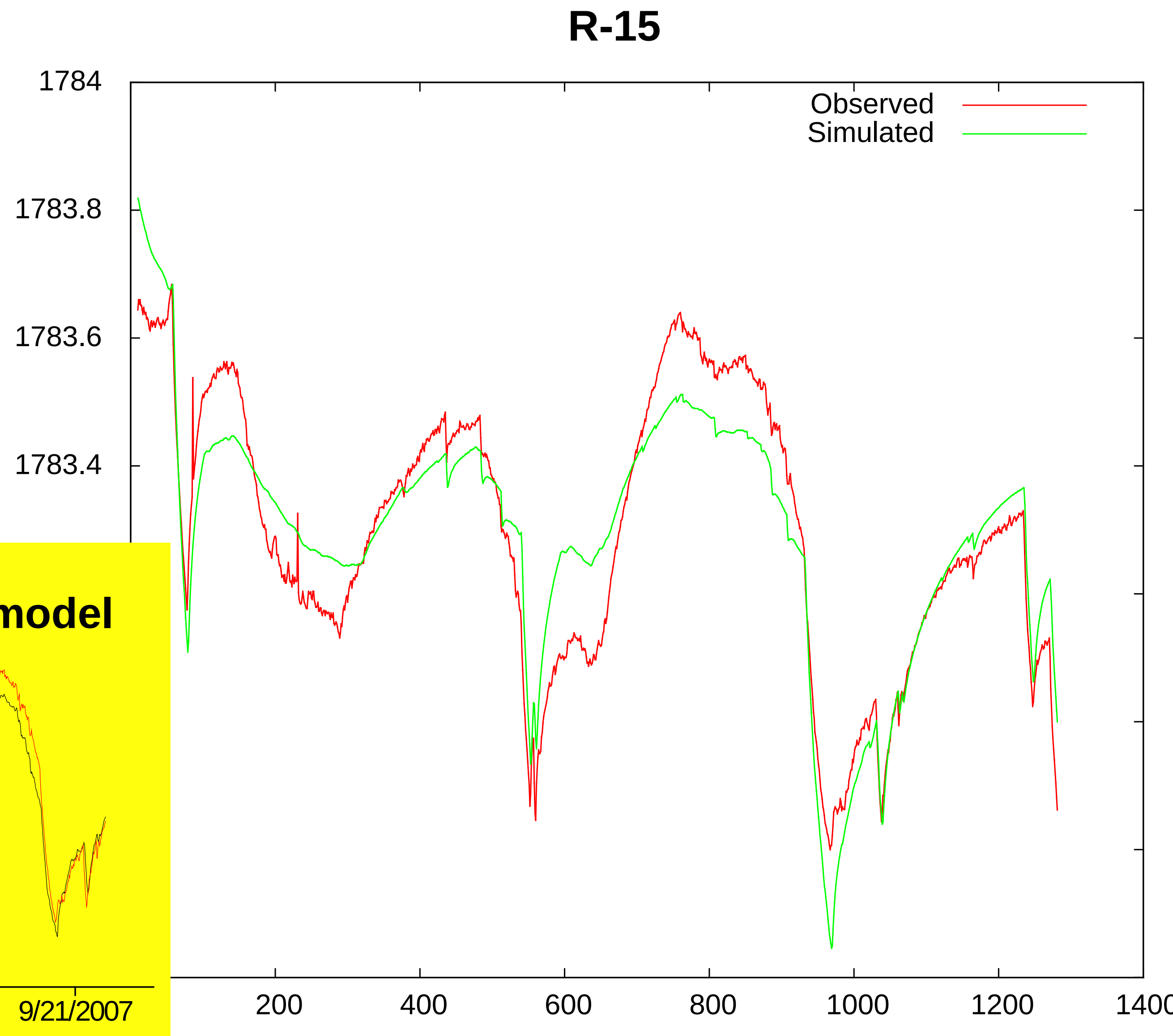
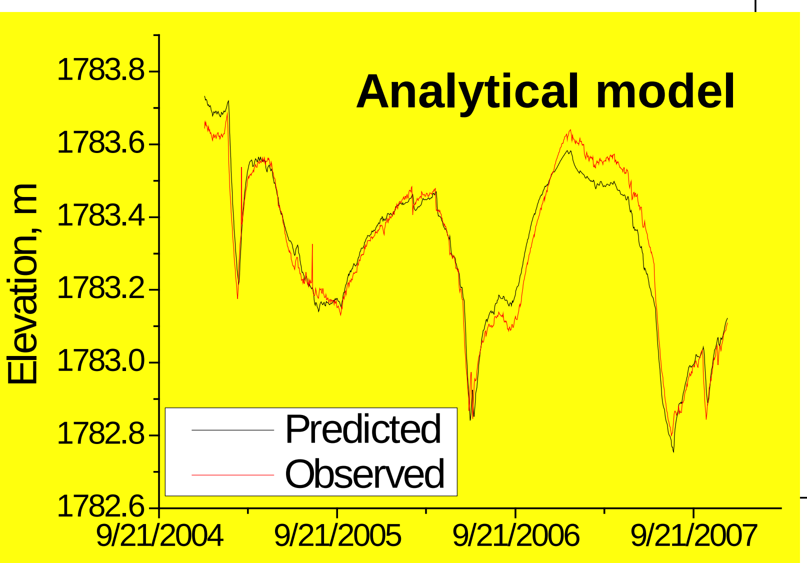
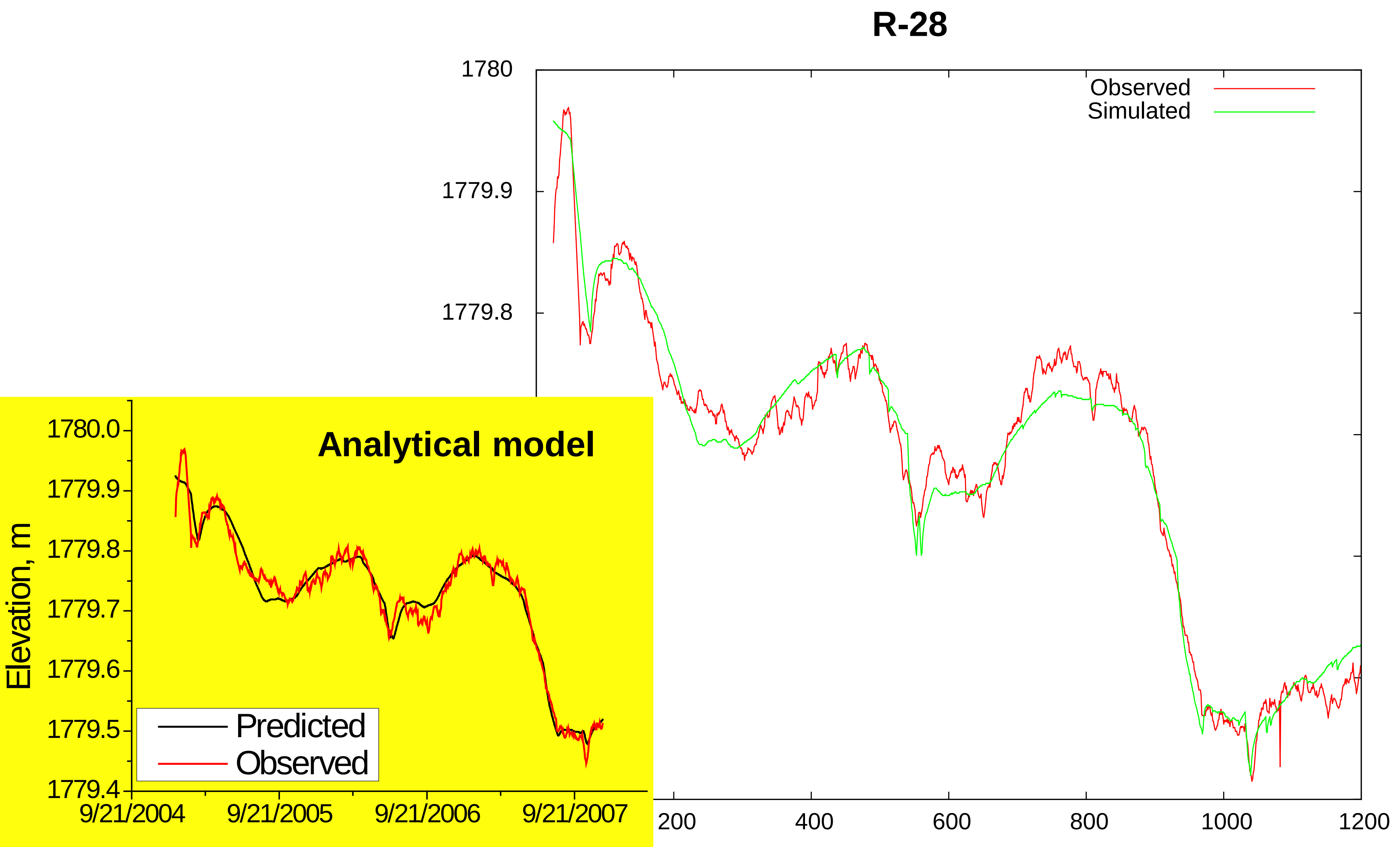




Inverse results using numerical model

How accurately can the numerical model reproduce observed water-levels based on the pumping records of all the water-supply wells?

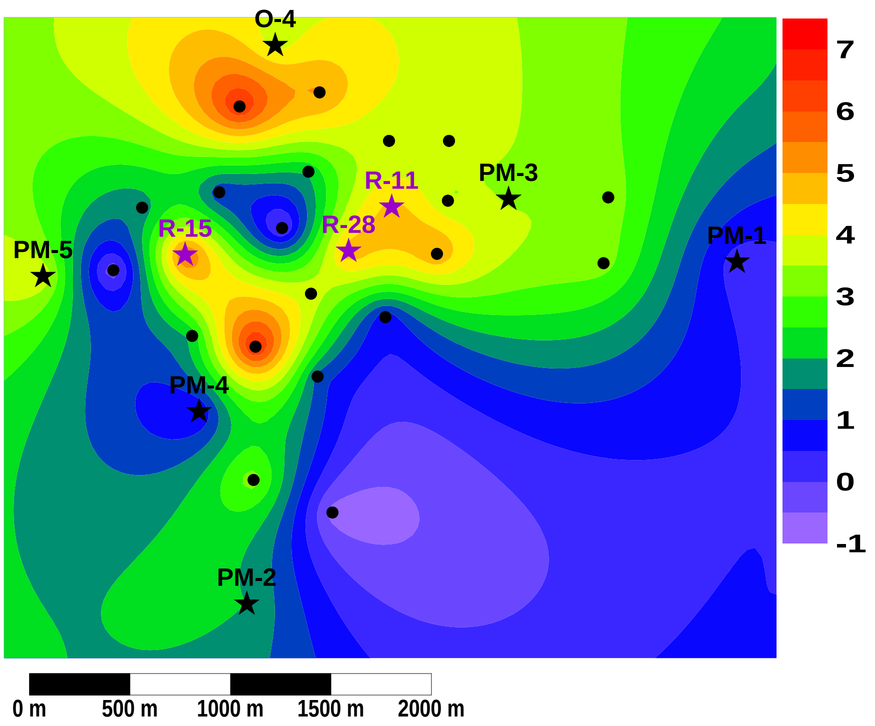


Tomographic estimates of aquifer spatial heterogeneity (single realization from a series of alternative possible solutions)

- ~3000 calibration targets (there is data redundancy)
- 57 pilot points; 117 adjustable parameters (in this case)

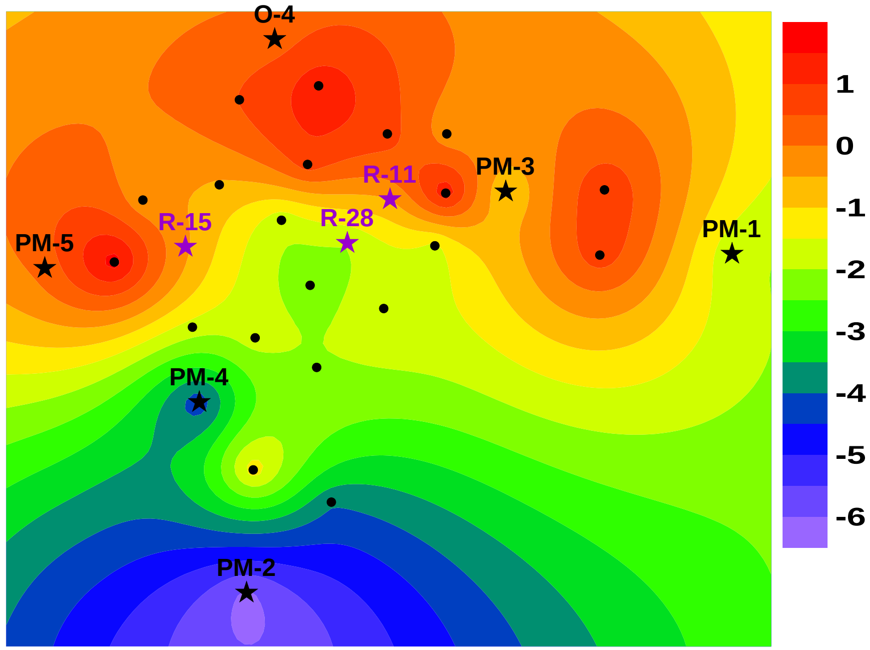
Transmissivity (T)

$\log_{10}$ T [m^2/d]



Storativity (S)

$\log_{10}$ S [-]

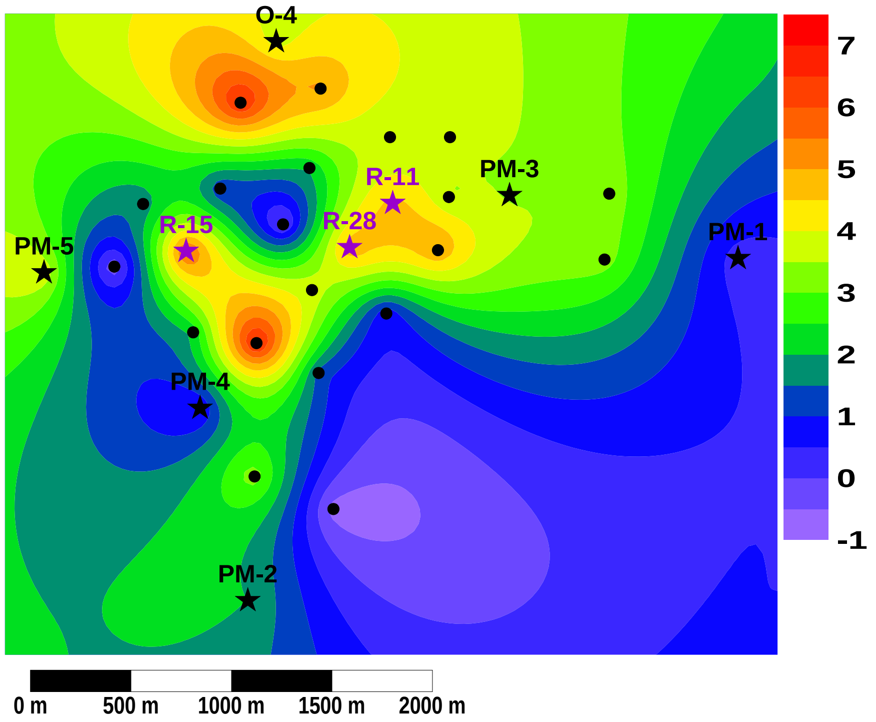


Legend: black stars – pumping wells; purple stars -- observation wells; black dots – pilot points

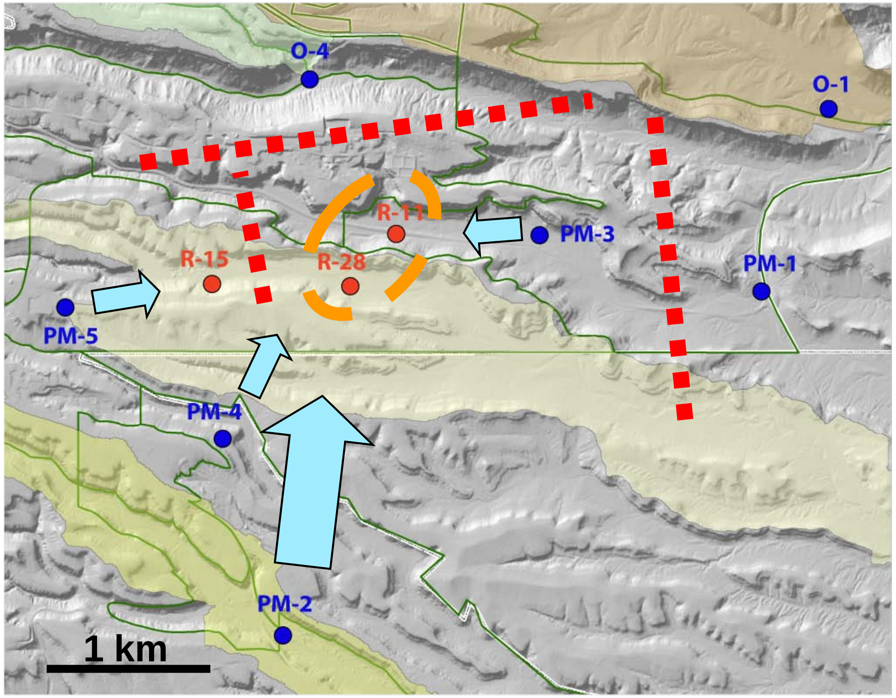
Estimated aquifer spatial heterogeneity

Tomographic estimate of transmissivity (T)

$\log_{10} T$ [m^2/d]



Aquifer structure deduced from the analytical analyses



$\log_{10} T$ [m^2/d]	Uniform (analytical) analysis							
	PM-1	PM-2	PM-3	PM-4	PM-5	O-1	O-4	Tomo-graphic analysis
R-11	-	3.5	4.0	3.2	-	-	-	
R-15	-	3.3	3.4	3.2	3.7	-	-	
R-28	-	3.5	3.8	3.7	-	-	-	
						Mean	3.5	3.0
						Variance	0.069	2.1

$\log_{10} S$ [-]	Uniform (analytical) analysis							
	PM-1	PM-2	PM-3	PM-4	PM-5	O-1	O-4	Tomo-graphic analysis
R-11	-	-1.5	-0.1	-1.1	-	-	-	
R-15	-	-1.9	-1.5	-1.7	-1.5	-	-	
R-28	-	-1.5	-0.4	-1.2	-	-	-	
						Mean	-1.2	-1.7
						Variance	0.4	2.8

Conclusions

Results are consistent with previous work related to scaling effects of aquifer properties [e.g. Gelhar, 1993, Dagan and Neuman, 1997; Meier at al., 1998; Sanchez-Villa, 1999; Vesselinov at al., 2001, etc.]

- **Compared to the non-uniform analyses, uniform analyses overestimate the mean aquifer properties, and underestimate the aquifer heterogeneity (variances)**
- **Uniform case: variability in T suggests pronounced aquifer heterogeneity (non-stationarity)**
- **Uniform case: var(S) > var(T). Non-uniform case: var(T) ≈ var(S); var(S) is still substantial (this may be real or caused by 3D or other effects unaccounted in the conceptual model)**

Conclusions (cont.)

- Tomographic analysis based on <u>long-term</u> (3 year) production and water-level records is successfully applied to extract information about the <u>large-scale</u> properties of the regional aquifer
- Pumping influences of individual pumping wells are fingerprinted despite the small magnitudes of observed drawdowns
- Analysis of the results based on a simple analytical model suggests that there may be large-scale hydrogeologic structures (faults and troughs) with contrasting aquifer properties
- Similar estimates of aquifer heterogeneity are also obtained using the tomographic analysis based on numerical model
- Information content of the data collected during previous pumping tests (at PM-2, PM-4) <u>is much inferior to</u> the information content of the data collected during long-term water-supply pumping
- This is a novel and unique research work; similar analyses have not been previously published in the hydrogeologic literature

Potential future work:

- Include longer water-level/pumping records and more monitoring wells
- Evaluate uncertainty in estimates of aquifer heterogeneity
- Extend the analysis to 3D tomography