Cost-Effective and High-Resolution Subsurface Characterization through Integration of Sequential Pumping Test Data

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Presentation at RemTech 2014, Banff, Calgary, Canada
October 15, 2014

Background

- When is heterogeneity important?
  - Water supply issues?
    - Quantification of groundwater storage in aquifers/aquitards;
    - Well head protection (3D capture zones);
    - Aquifer Storage and Recovery (ASR), etc.
  - Prediction of solute/contaminant transport
    - Active remediation (e.g., pump-and-treat; amendment injection) of various contaminants;
    - Passive remediation (e.g., bioremediation, natural attenuation);
    - In situ leaching of metals;
    - Waste disposal sites and injection of wastewater;
    - Mining sites.

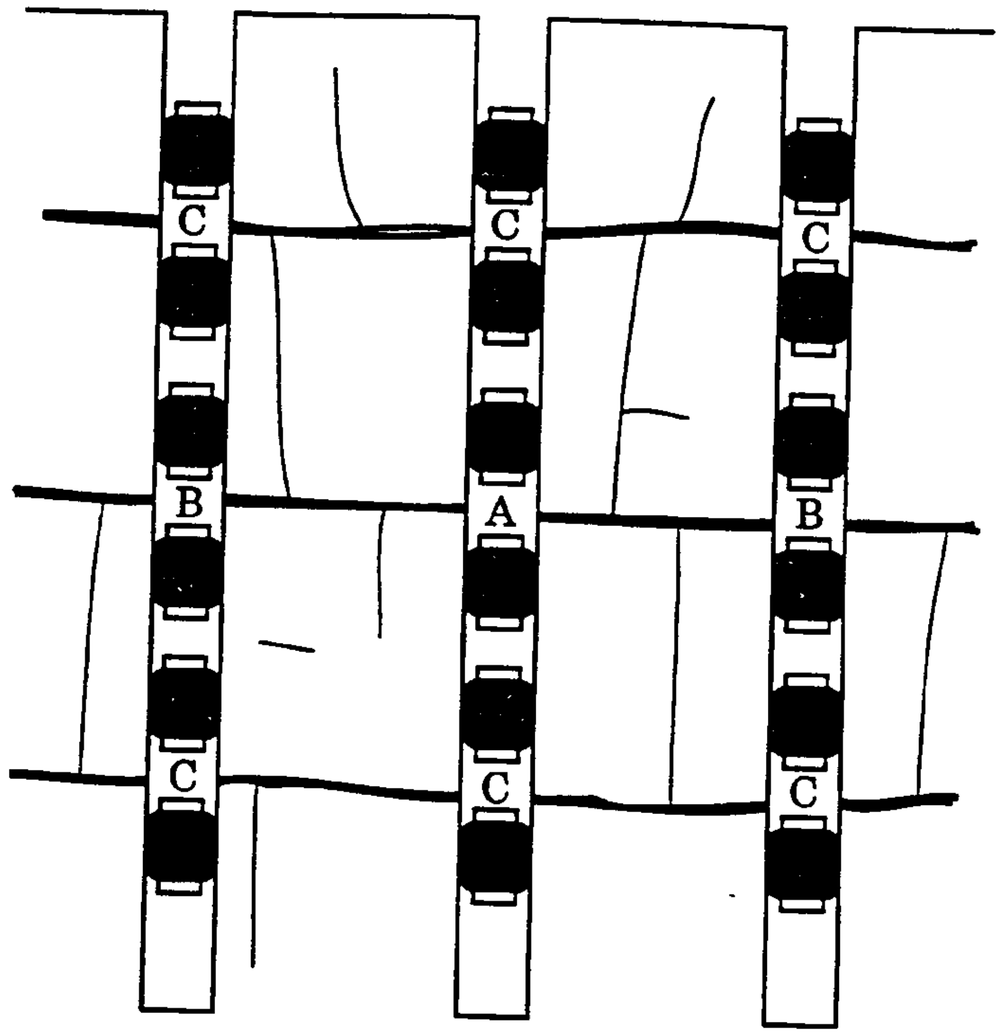
Background:

- When is heterogeneity important?
  - More efficient energy resource extraction:
    - Oil & gas;
    - Coalbed methane;
    - Uranium;
    - Geothermal, etc.
  - **Better “up-front” characterization of heterogeneity can lead to improved predictive capability of groundwater flow and transport models (also resource extraction models).**

Hydraulic Tomography:

A new method of subsurface mapping of heterogeneity in hydraulic parameters

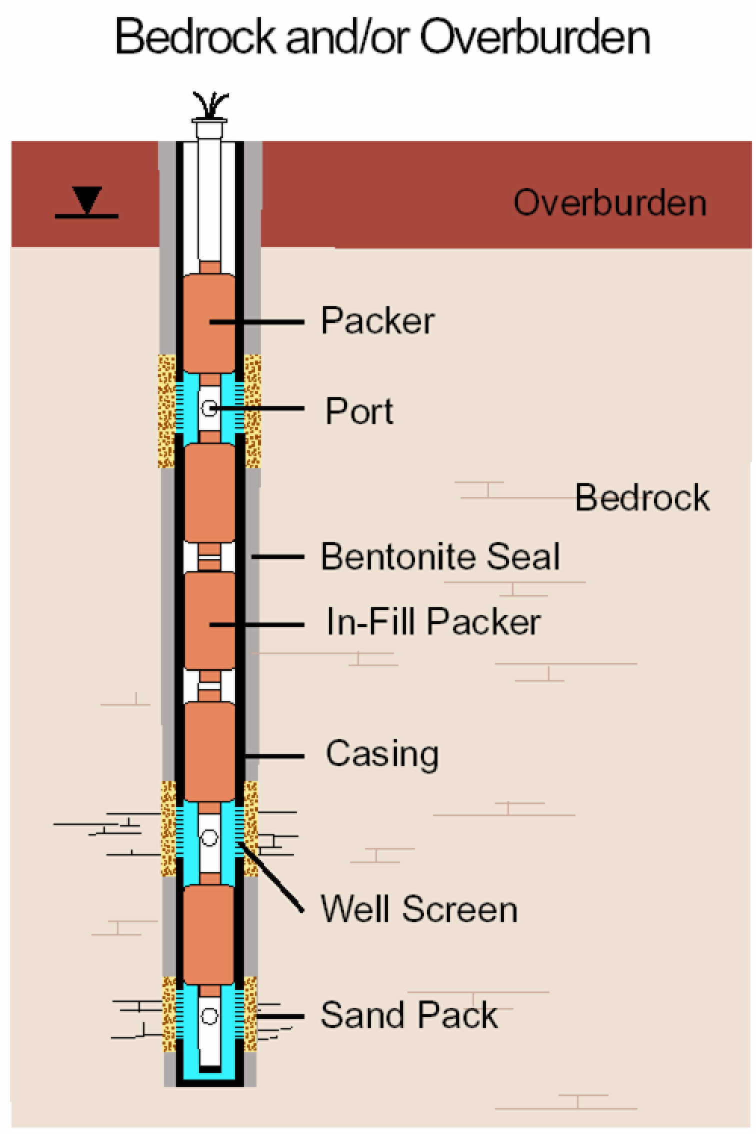
- Utilizes several pumping tests and corresponding drawdown measurements;
- Use inverse groundwater flow model to estimate K and S_s heterogeneity and its uncertainty;
- Resolution depends on density of head measurements;
- Information on connectivity is also obtained.



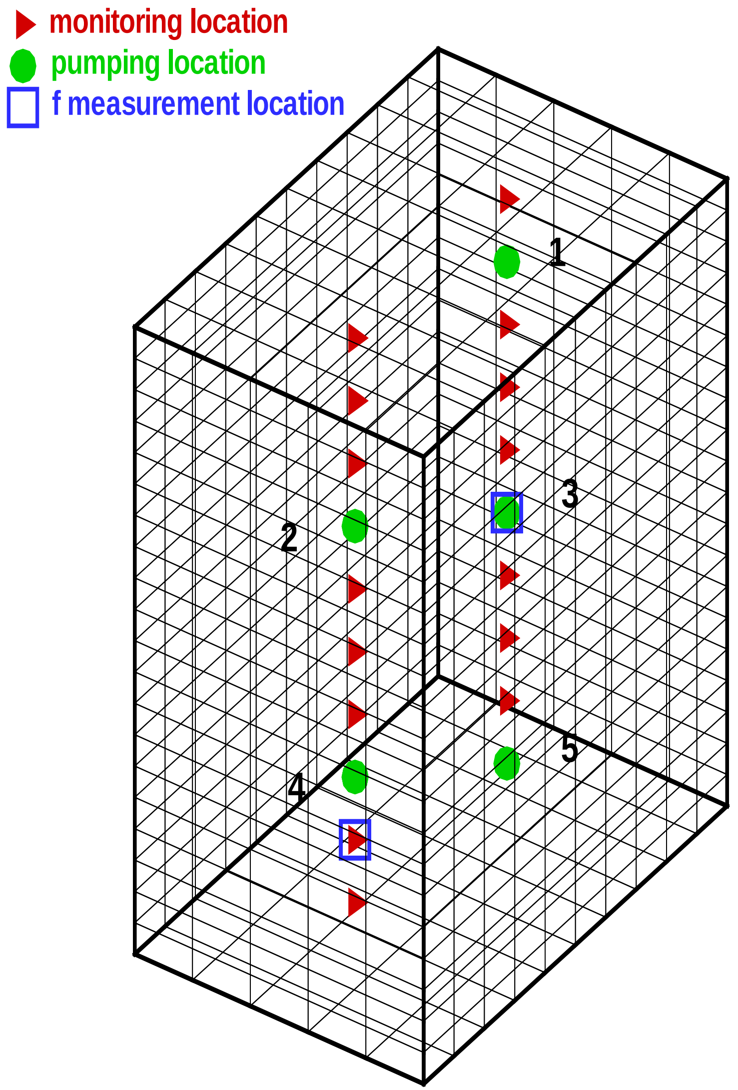
(*NRC*, 1996)

Computational Study of Hydraulic Tomography (HT)

Geostatistical inverse approach (Jim Yeh, University of Arizona)

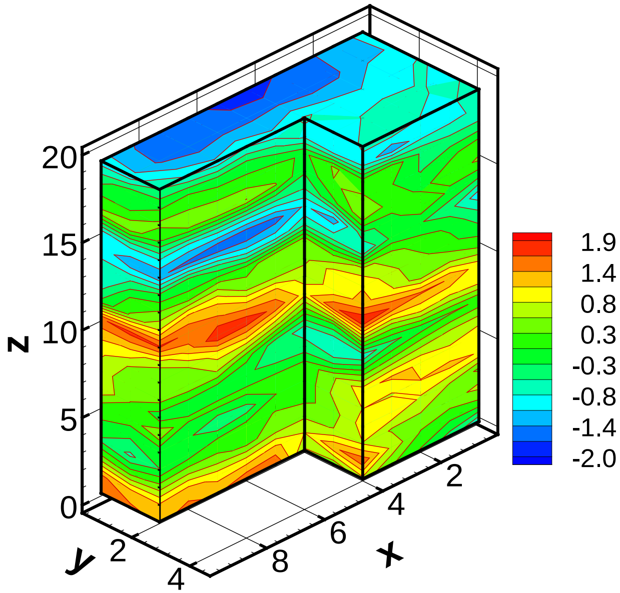


Permanent or Removeable Packers
in Casing or Well Screen

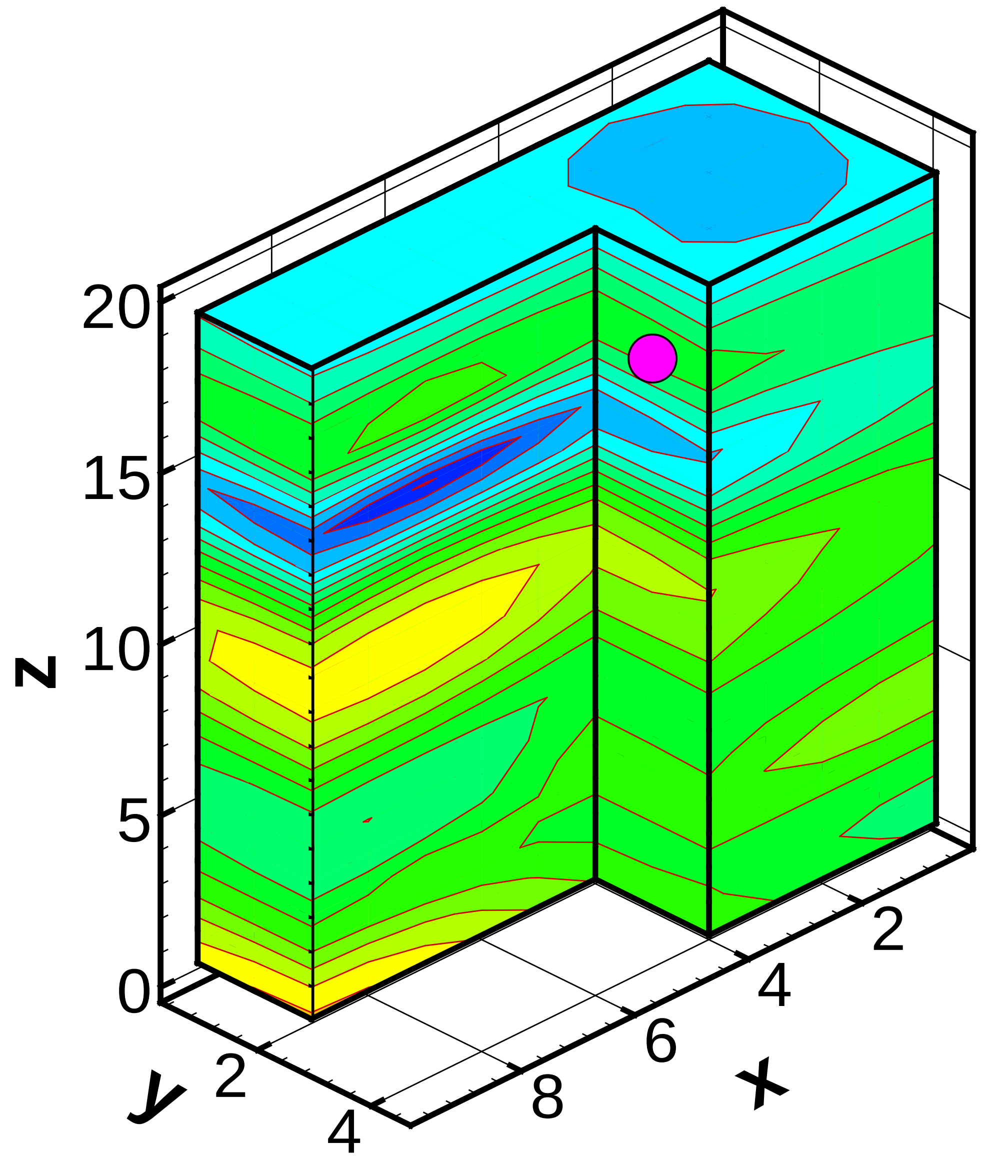


(*Yeh and Liu*, 2000)

“True” K field



“Estimated” K field after including data from 1 pumping test in the inverse model



Dimensions: 10 m x 5 m x 20 m-

Total elements: 1000

Geometric mean of conductivity: 0.35 m/hr

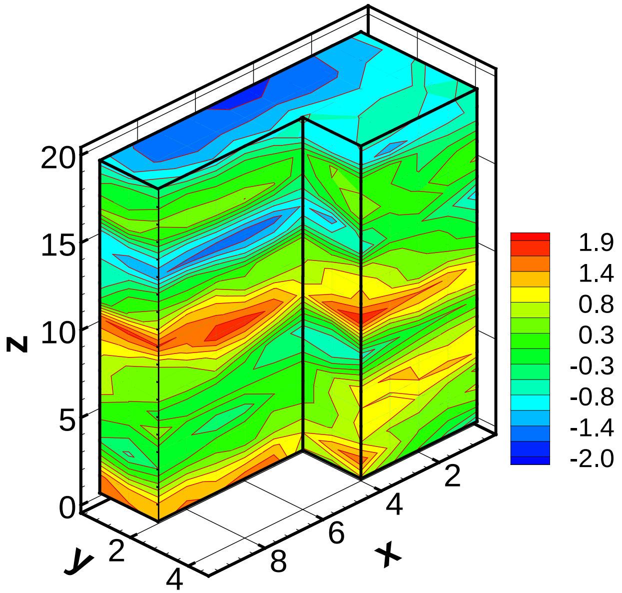
Variance of lnK = 0.63

Horizontal correlation scale (λ_x): 12 m

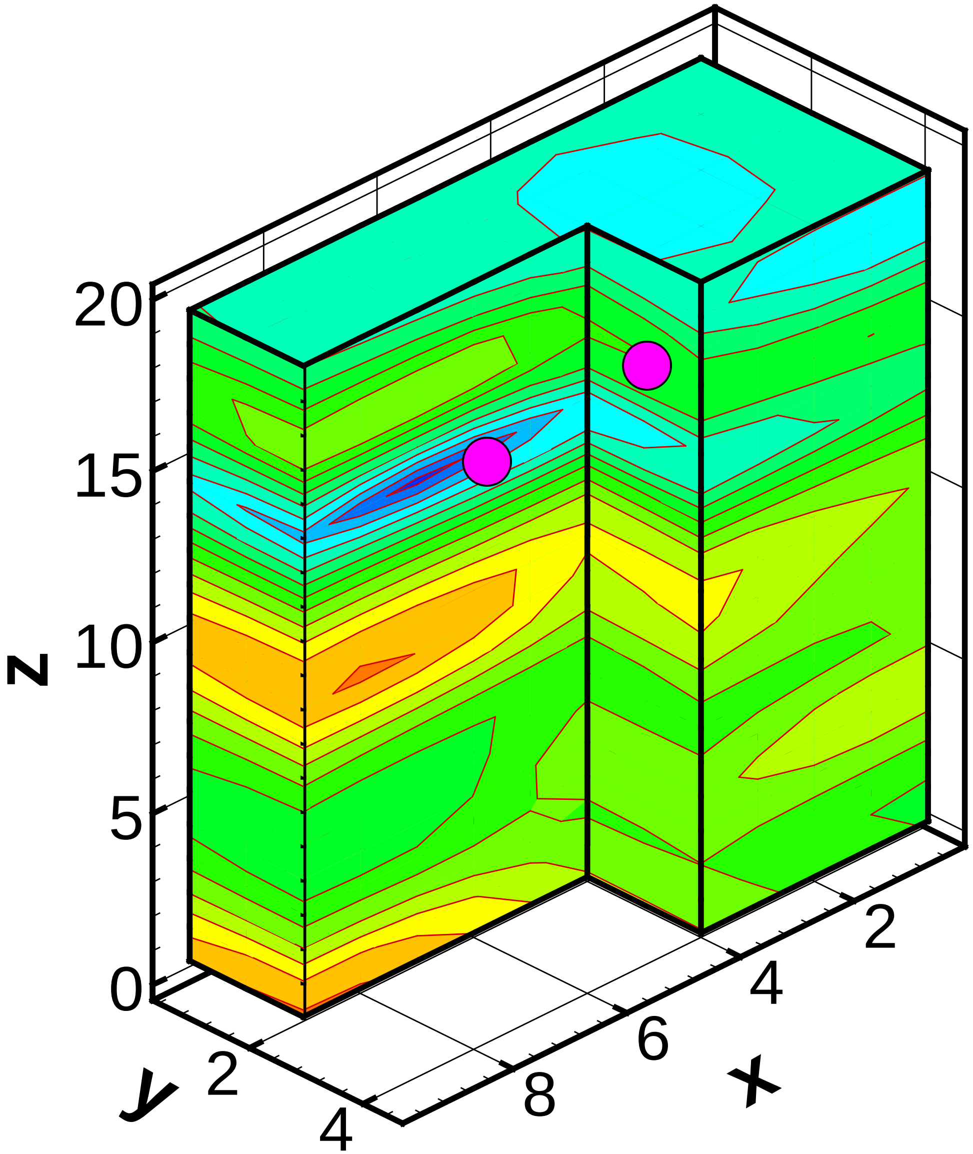
Vertical correlation scale (λ_z): 4 m

(*Yeh and Liu*, 2000)

"True" *K* field

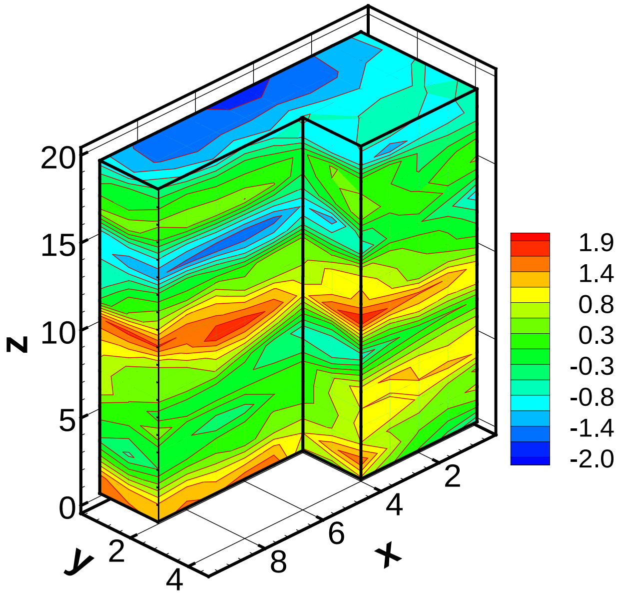


"Estimated" *K* field after including data from 2 pumping tests in the inverse model

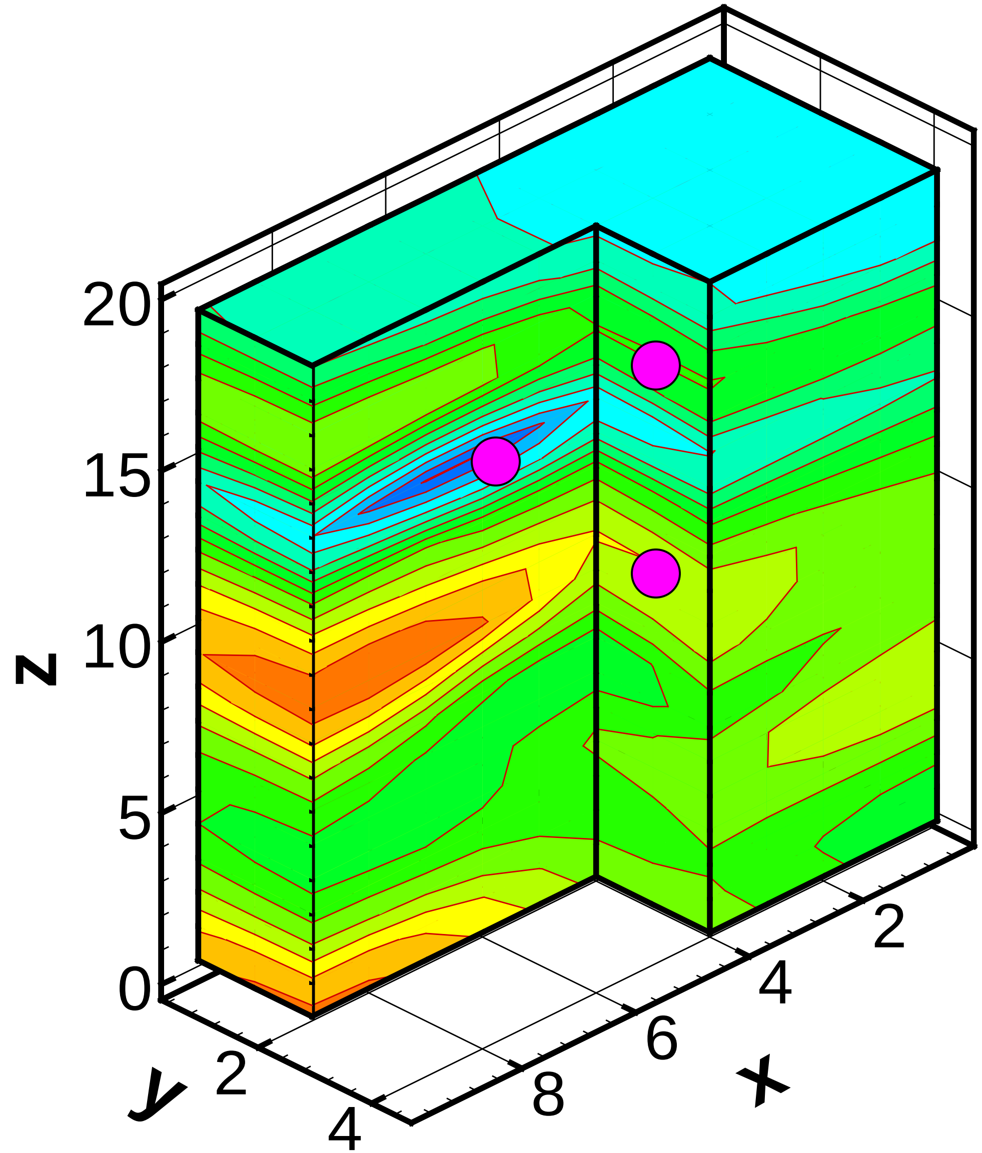


(*Yeh and Liu*, 2000)

“True” *K* field

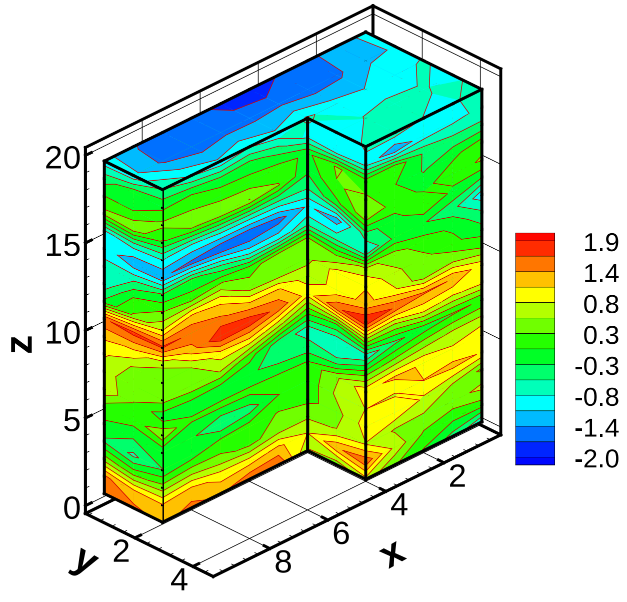


“Estimated” *K* field after including data from 3 pumping tests in the inverse model

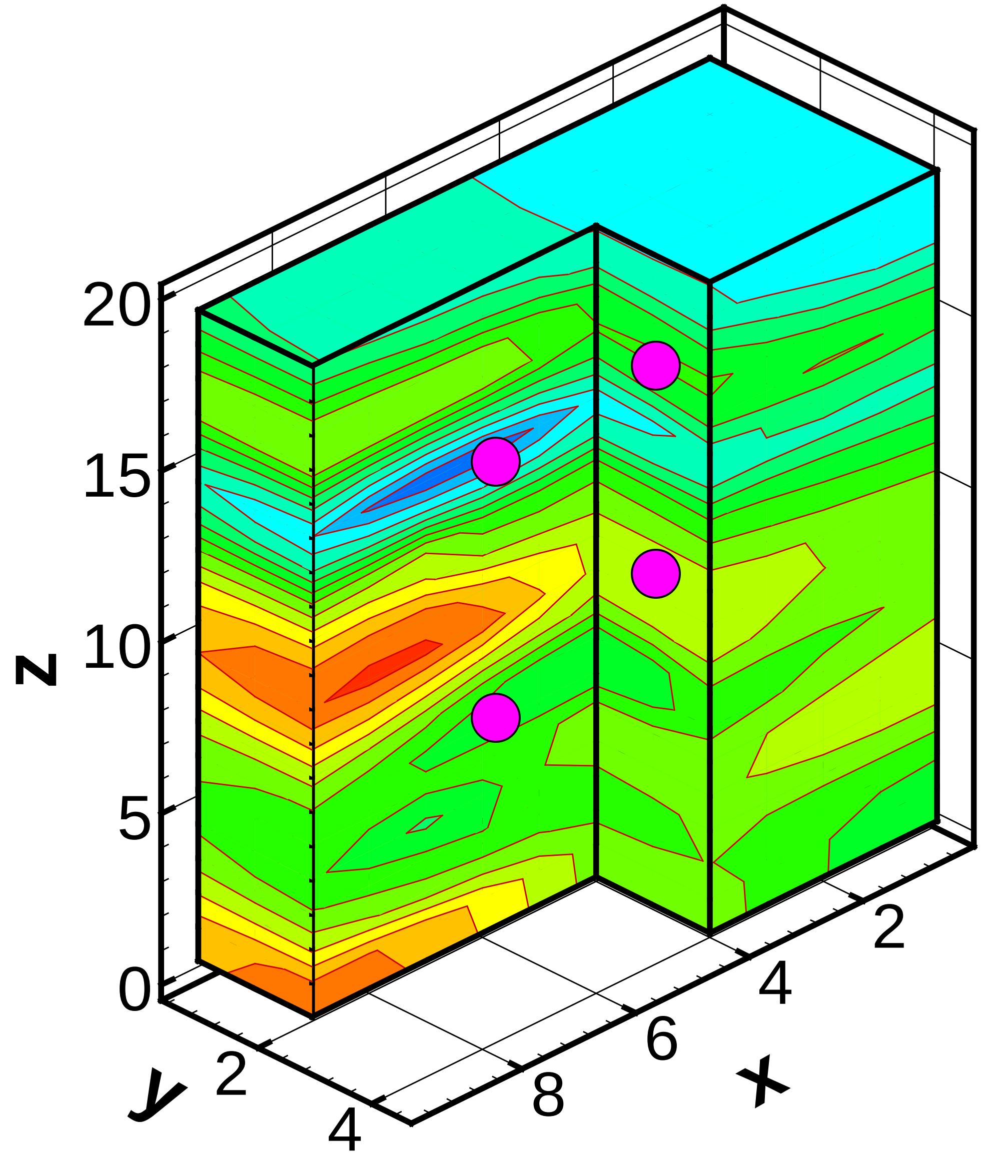


(*Yeh and Liu*, 2000)

"True" *K* field

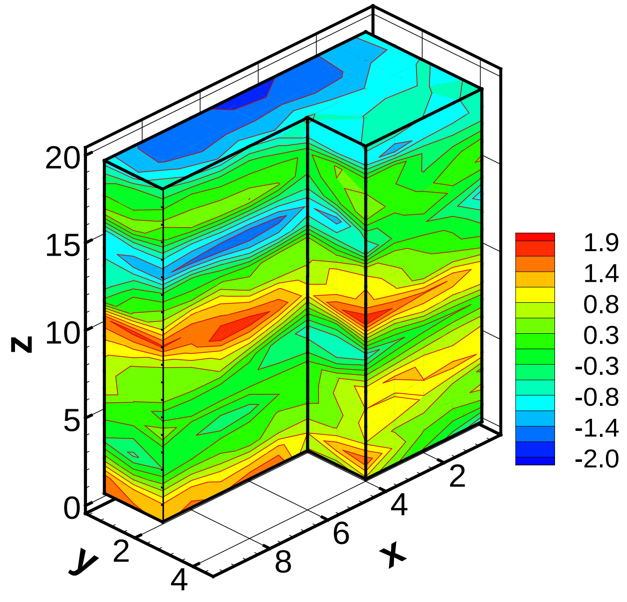


"Estimated" *K* field after including data from 4 pumping tests in the inverse model

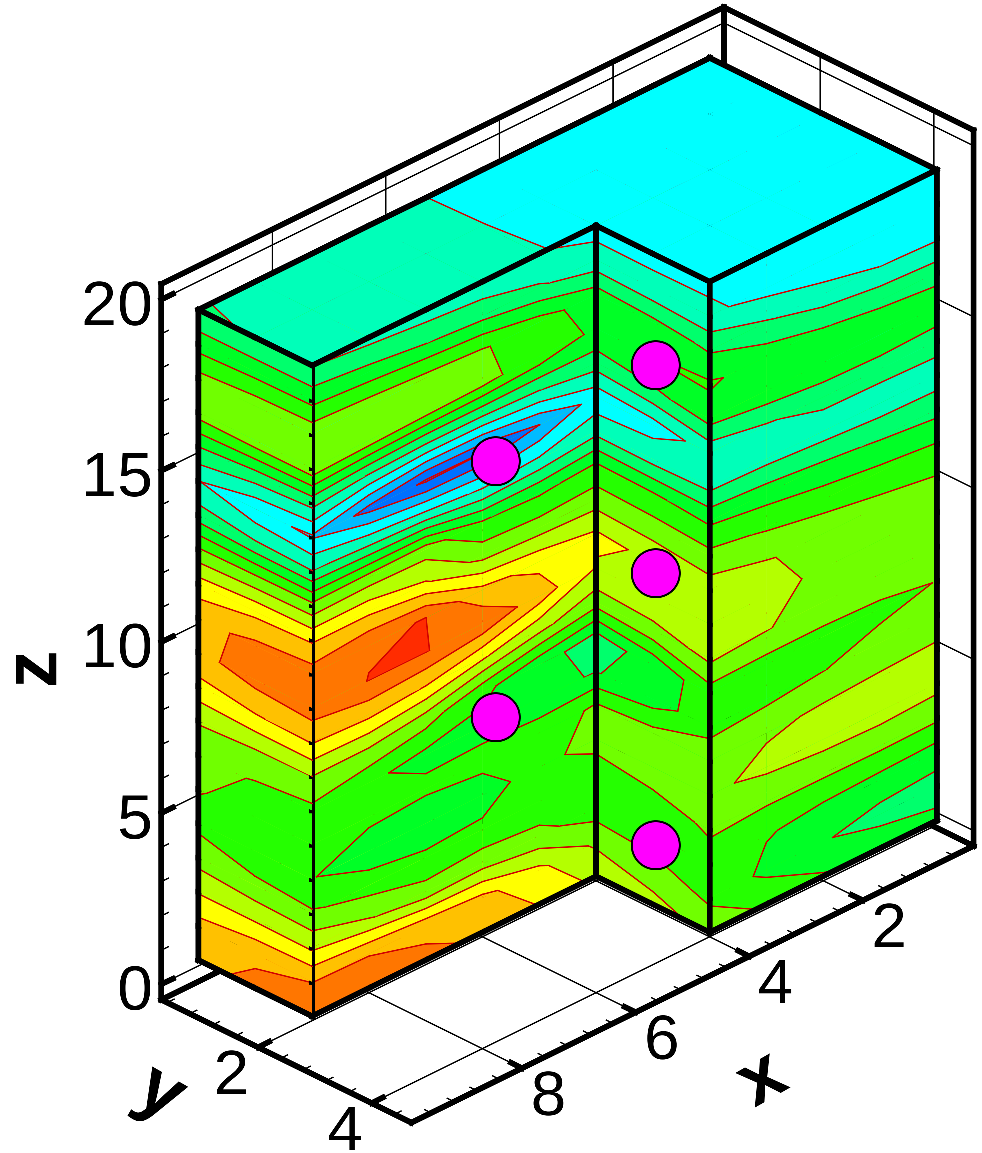


(*Yeh and Liu*, 2000)

“True” *K* field



“Estimated” *K* field after including data from 5 pumping tests in the inverse model

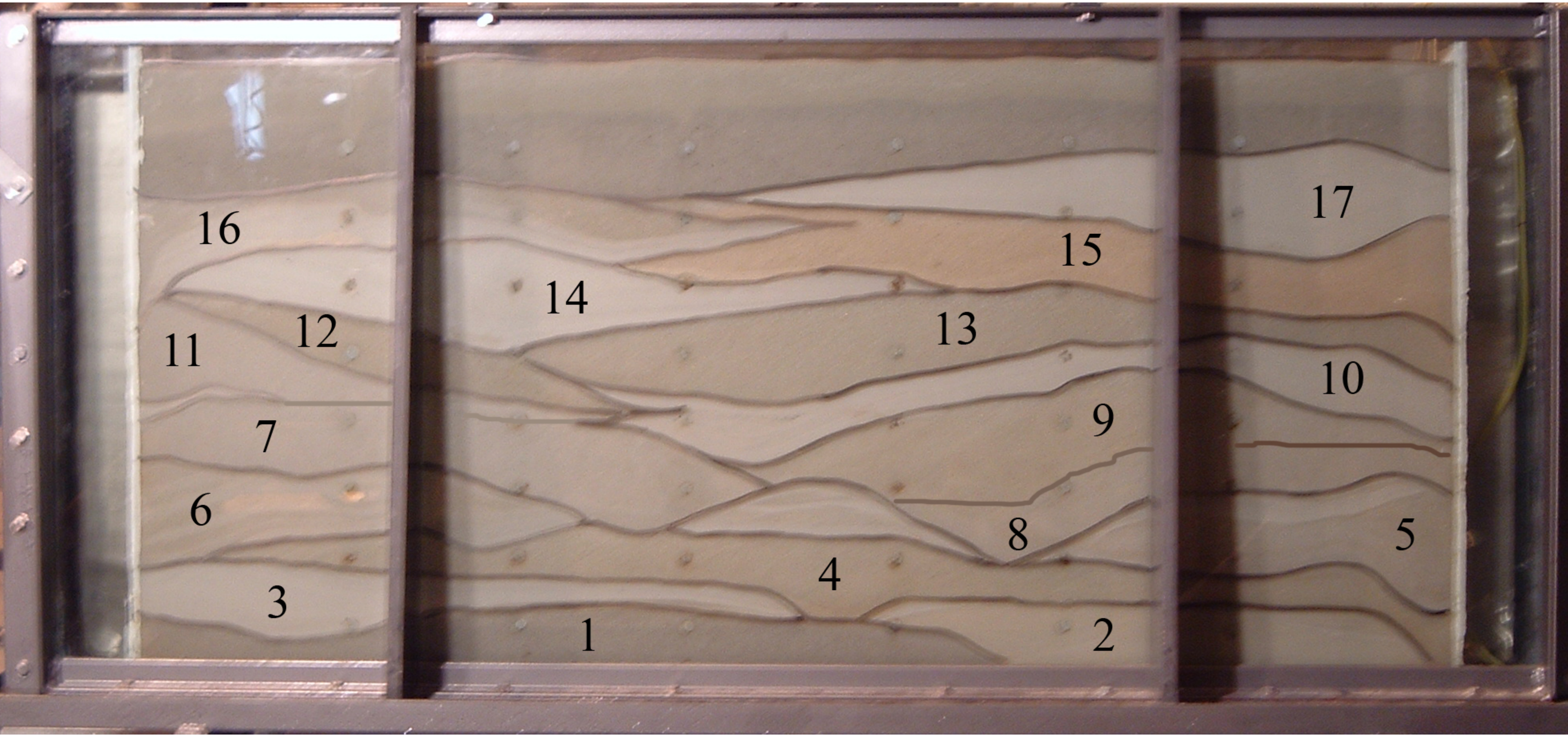


(*Yeh and Liu*, 2000)

Laboratory sandbox study of Hydraulic Tomography (HT)

- Performance assessment of various methods of capturing subsurface heterogeneity using a synthetic heterogeneous aquifer in the laboratory;
- Obtain K, S_s estimates (effective parameters & heterogeneous distributions);
- Test these estimates;
- How to test various characterization approaches?
  - Construct various transient groundwater models (homogeneous and heterogeneous) and;
  - Independent simulation of 16 pumping tests and quantitative comparison of results.

Synthetic heterogeneous aquifer



17 layers deposited by cyclic flux of sediment – laden water flowing from left and right orfices

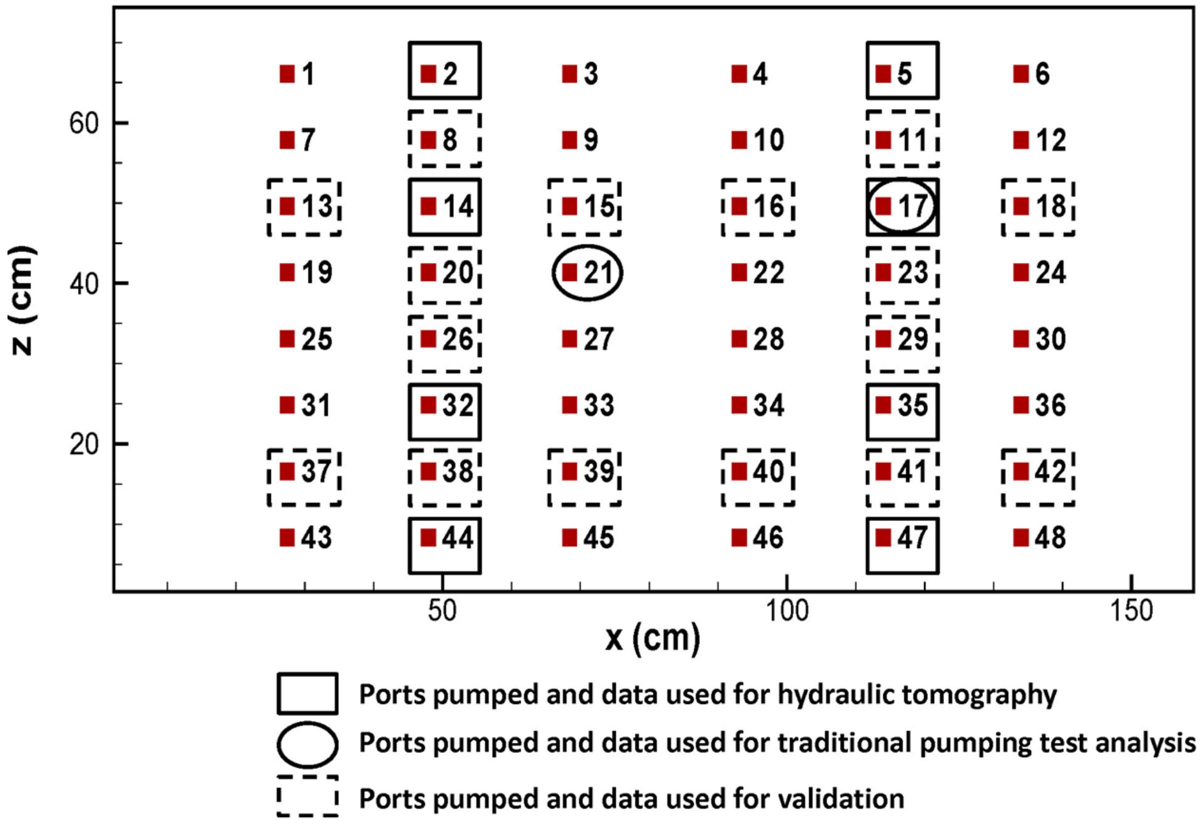
Laboratory validation of heterogeneous aquifer characterization approaches

Aquifer characterization methods:

- 48 single-hole tests
- 2 cross-hole tests for traditional analysis
- 8 cross-hole tests for hydraulic tomography

Validation of *K, S_s* estimates:

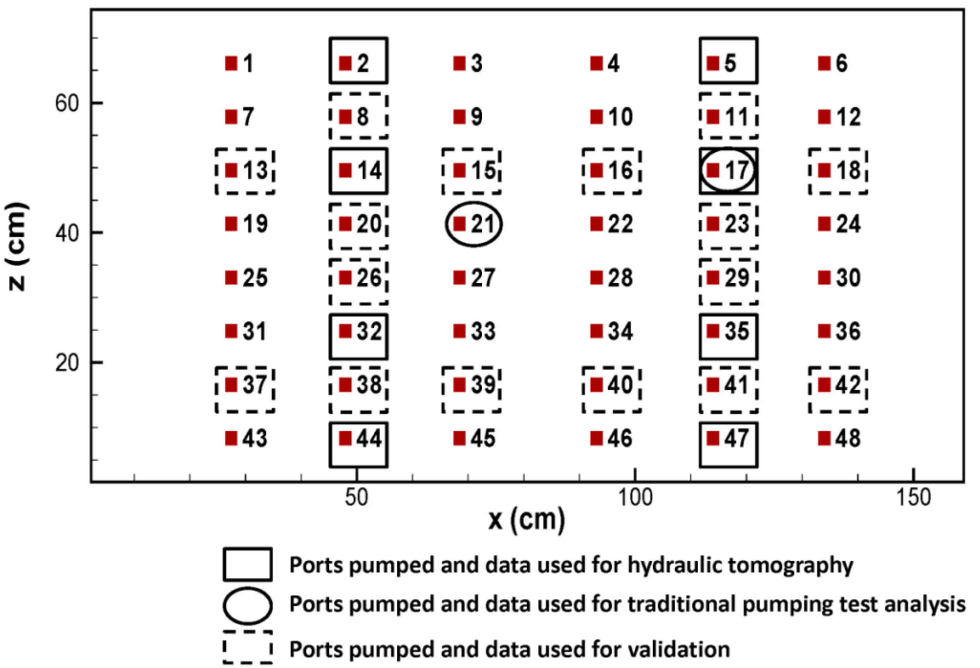
- simulation of 16 independent cross-hole tests and comparison to actual data



(*Berg and Illman*, 2011a)

Performance testing of various characterization approaches

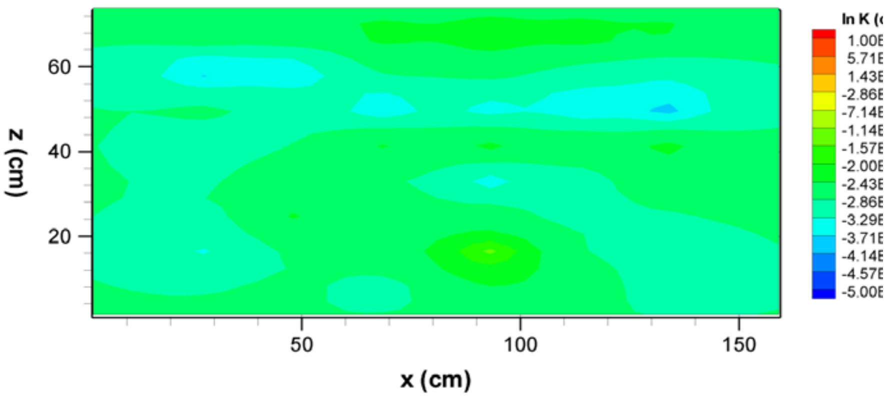
- Simulate 16 additional cross-hole pumping tests with 48 monitoring points using:
  - Homogeneous fields:
    - Geometric mean (K_G & S_{sG}) of single- and cross-hole K & S_s data;
  - Heterogeneous fields:
    - Kriged fields of single-hole K & S_s data;
    - Heterogeneous geological model with homogeneous K & S_s data for each layer from single-hole data
    - K & S_s tomograms obtained from Transient Hydraulic Tomography (THT)

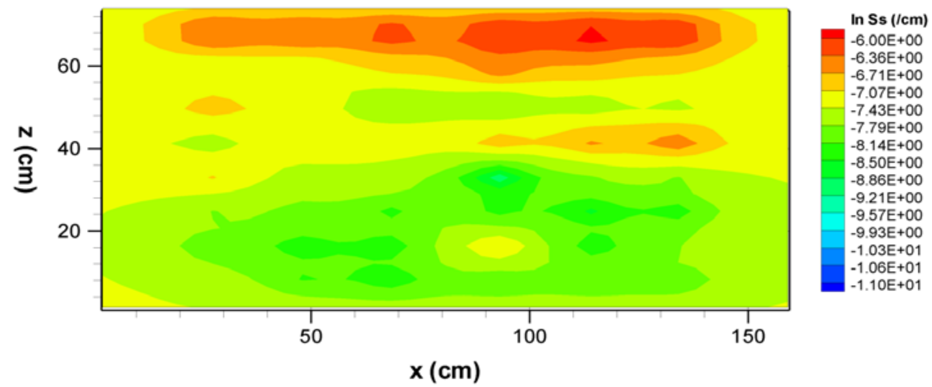


(*Berg and Illman*, 2011a)

Heterogeneous *K* & S_s Distributions
Geostatistical Analysis

Single-hole test data



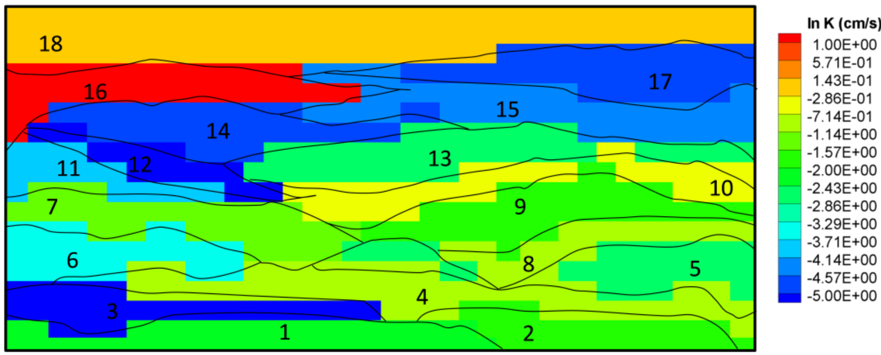


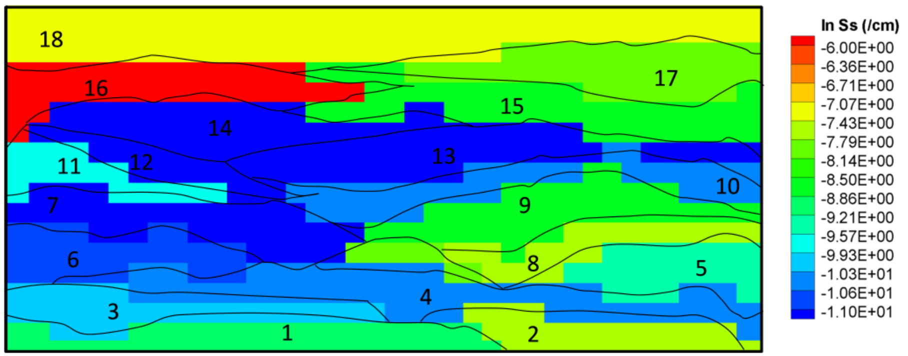
(*Berg and Illman*, 2011a)

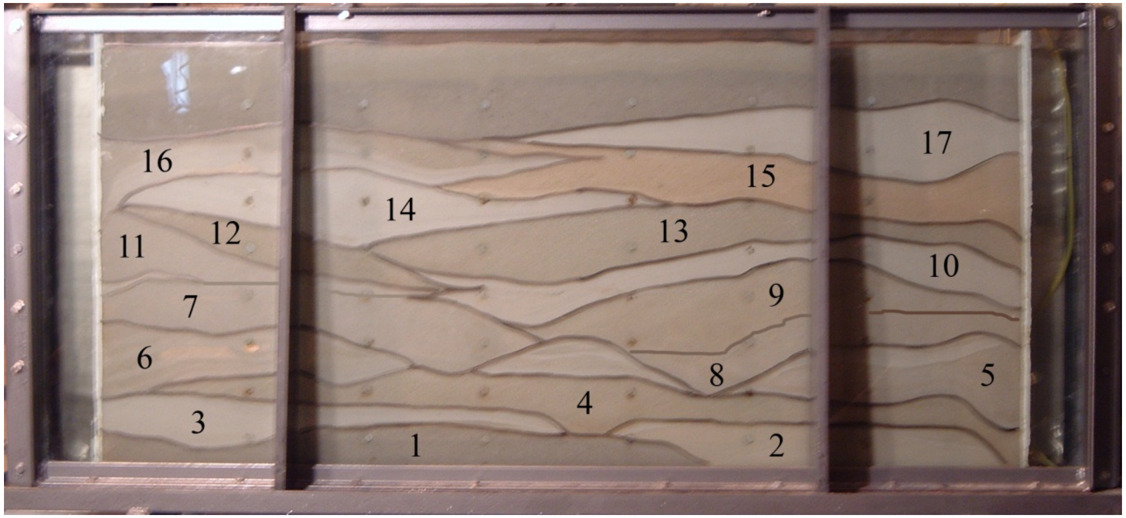
Heterogeneous K & S_s Distributions

Geological model that captures layers

Each layer has homogeneous K & S_s values



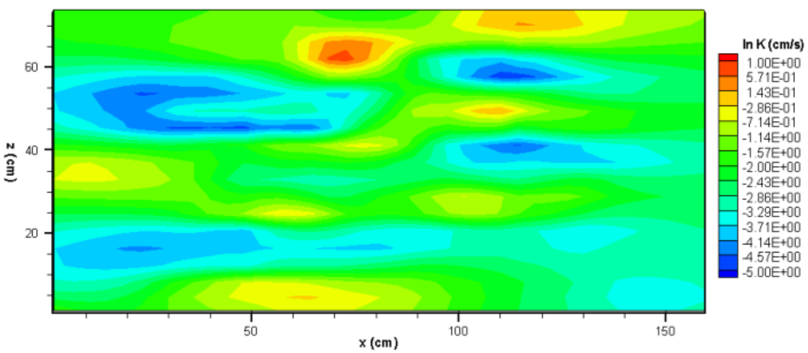


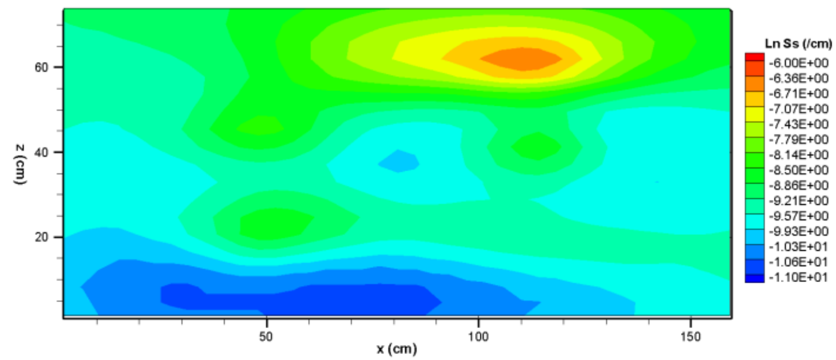


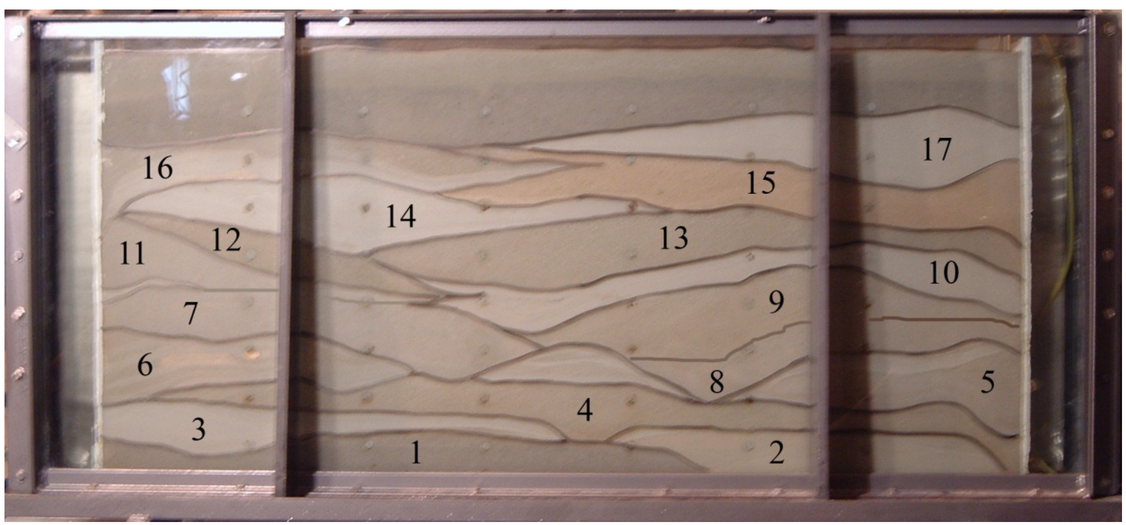
(*Berg and Illman*, 2011a)

Heterogeneous *K* & S_s Distributions (Tomograms): Transient Hydraulic Tomography

Data: 8 cross-hole tests



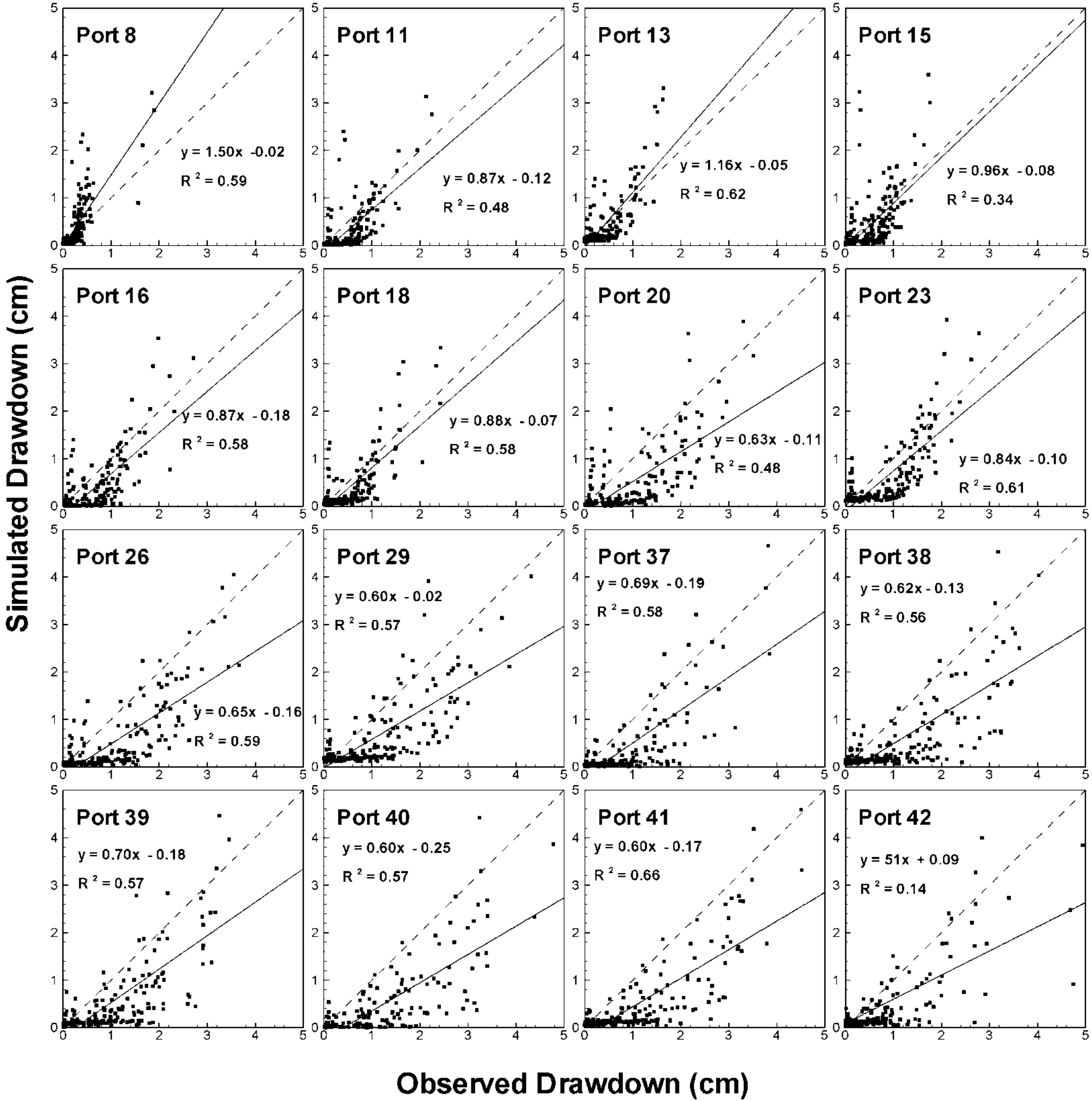




(*Berg and Illman*, 2011a)

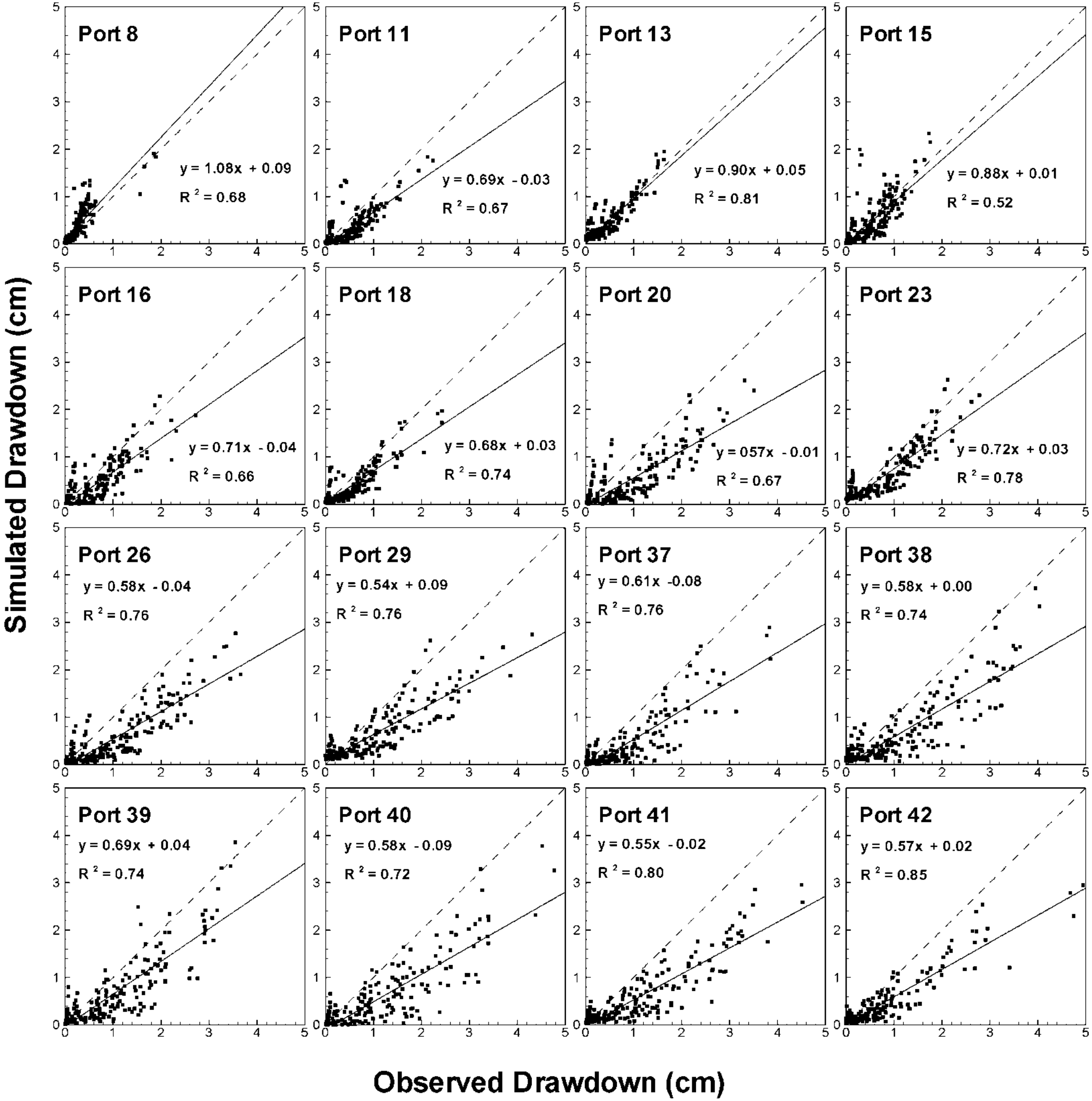
Groundwater model constructed with geometric mean of 48 single-hole K & S_s values

Comparison of simulated and observed drawdowns from 16 independent cross-hole tests (t = 0.5, 2, 5, and 10 secs)



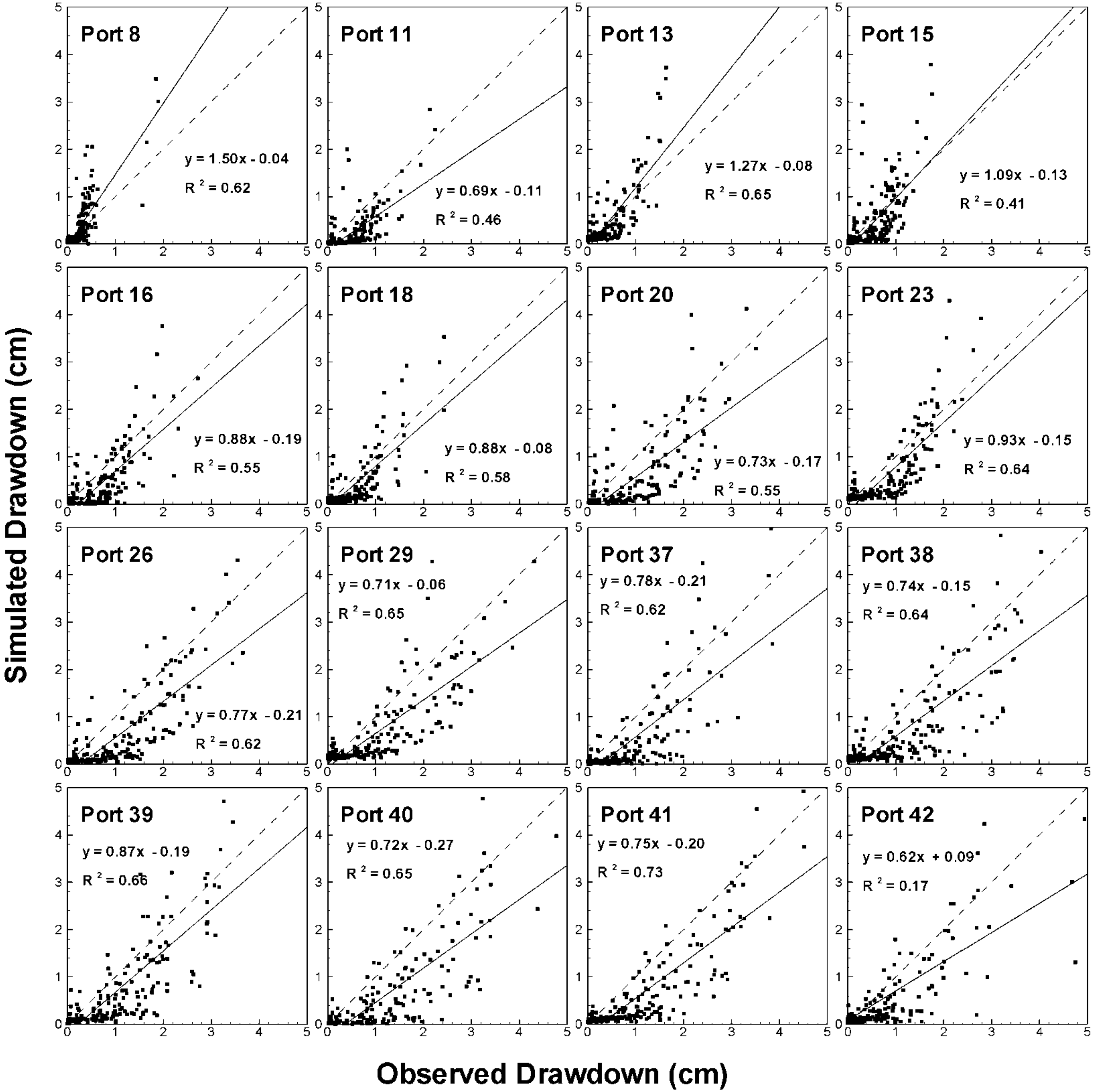
(*Berg and Illman*, 2011a)

Groundwater model constructed with geometric mean of 48 cross-hole equivalent K & S_s values from pumping test at port 21



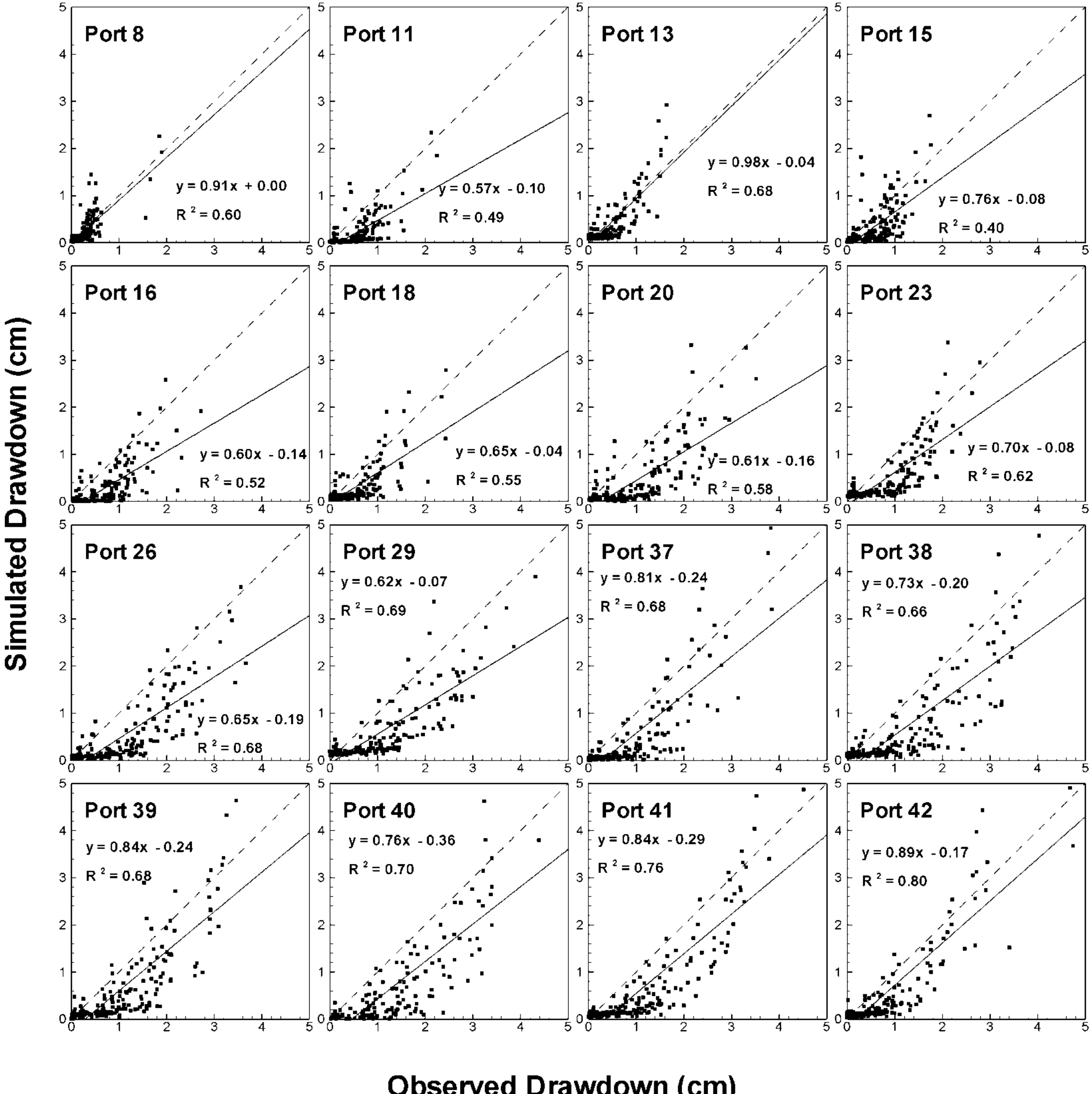
(*Berg and Illman*, 2011a)

Groundwater model constructed with kriged K & S_s values from 48 single-hole tests



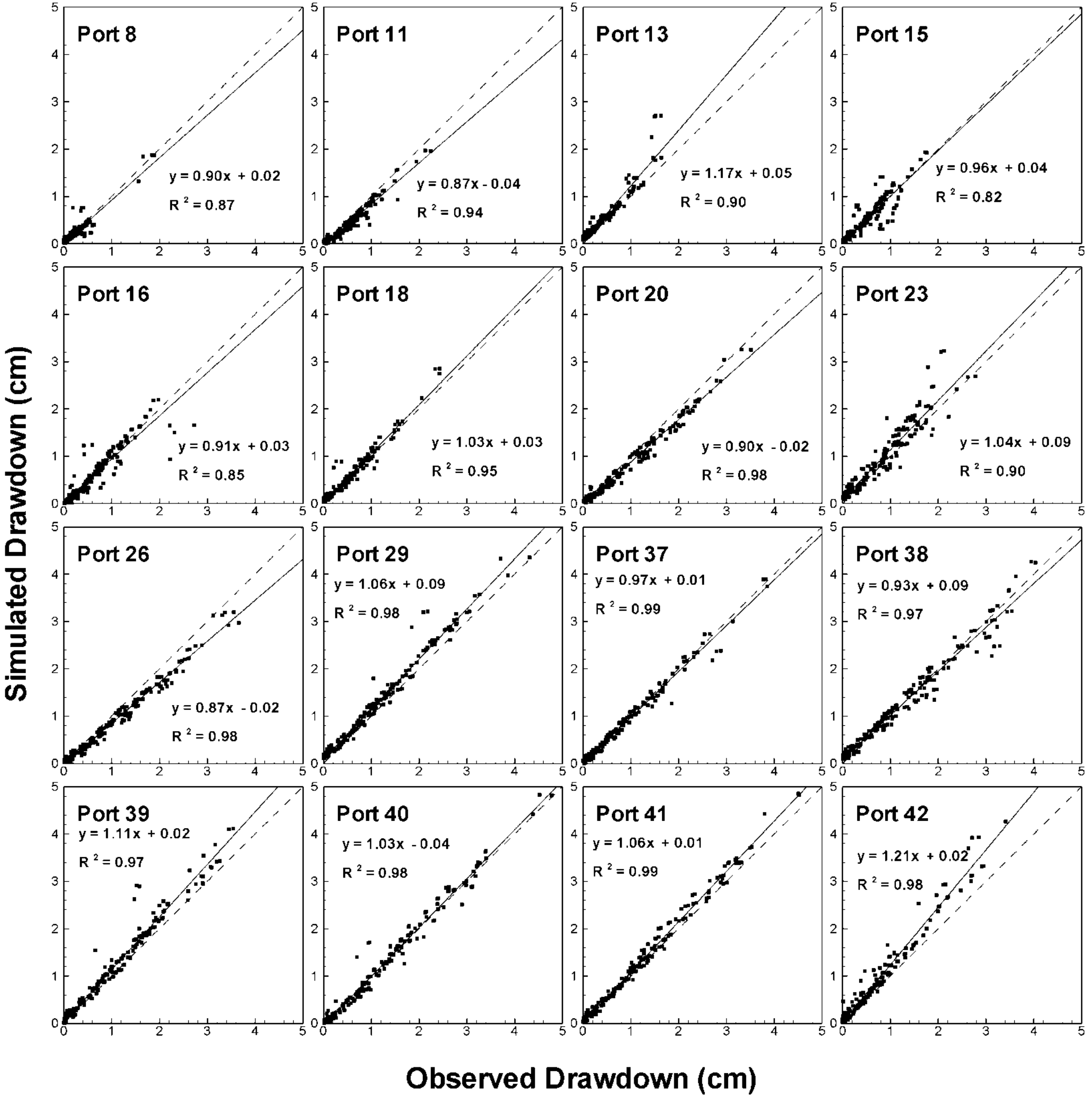
(*Berg and Illman*, 2011a)

Groundwater model constructed with each layer with homogeneous K & S_s values accurately built in (i.e., geological model)



(*Berg and Illman*, 2011a)

Groundwater model constructed with K & S_s values from Transient Hydraulic Tomography



(*Berg and Illman*, 2011a)

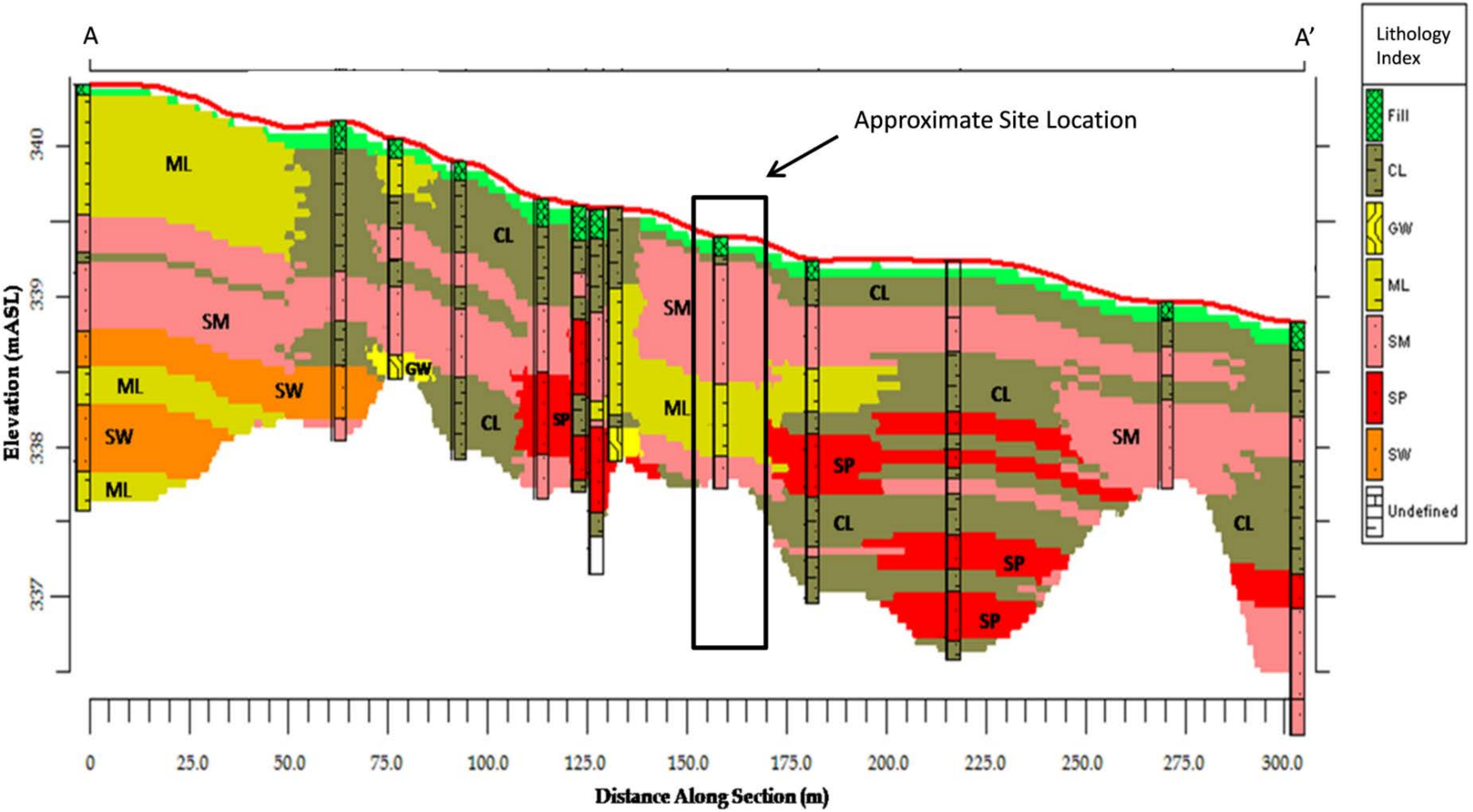
Take home message

- **Hydraulic tomography** clearly yielded the **best predictions** of drawdown responses from **independent pumping tests**
- Other approaches yield biased estimates of K and S_s which can affect predictions of pumping tests, contaminant transport, and remediation performance.
- Common criticism: This is a sandbox study.
- What about in the field when experimental conditions cannot be controlled as well in the lab?

Field study of Hydraulic Tomography (HT)

UW North Campus Research Site (NCRS)

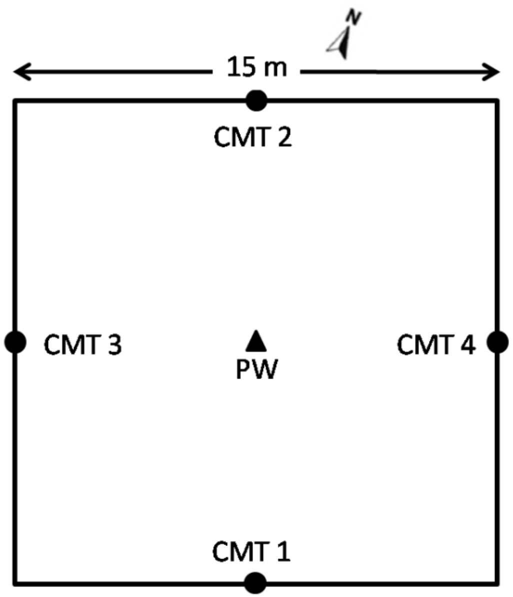
Cross-section of site geology



Fill = near surface material; CL=silty clay; GW = sandy gravel; ML = clayey silt; SP = sandy silt; SW = sand

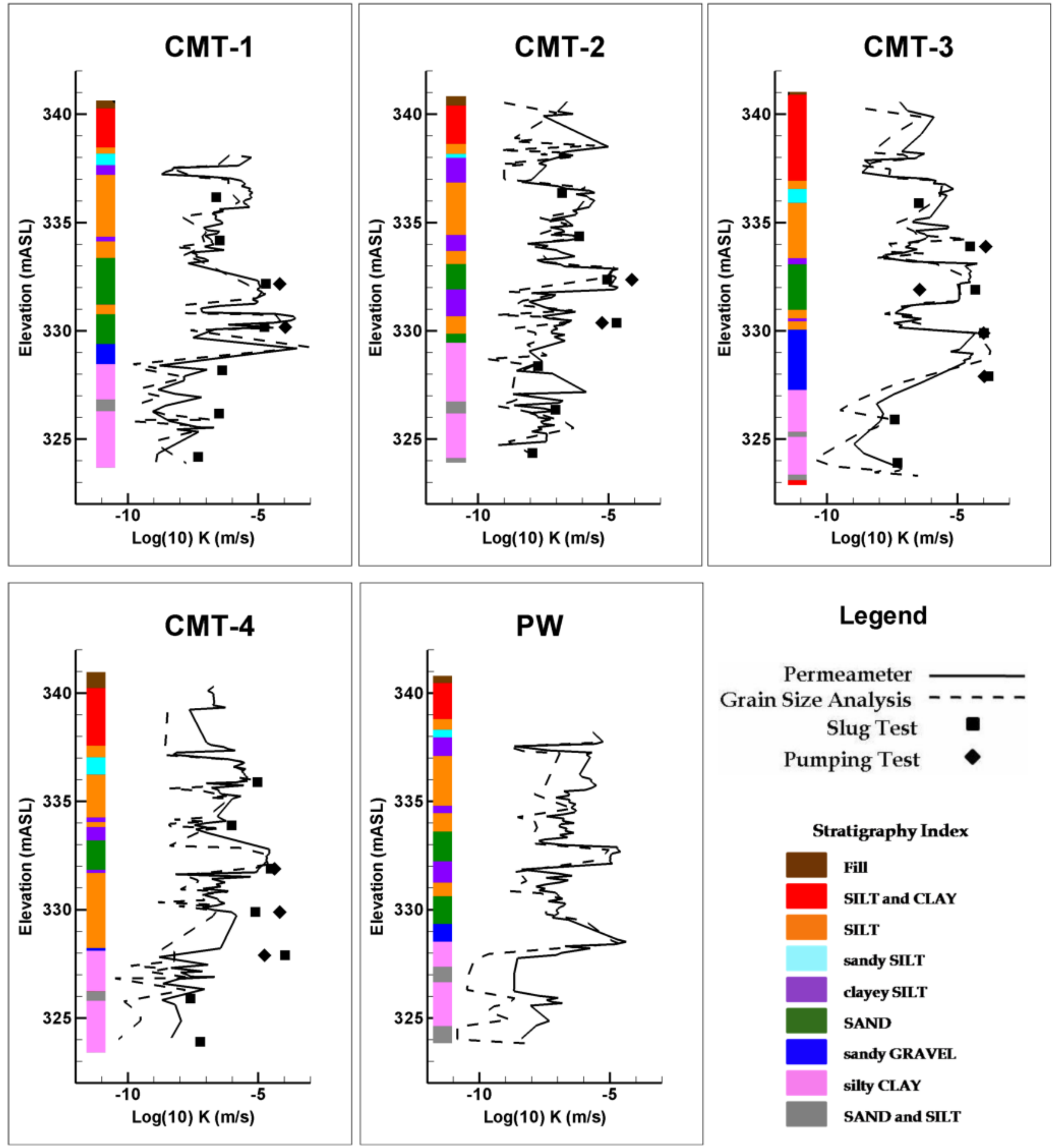
(*Alexander et al*., 2011; after *Sebol*, 2000)

Well layout and *K* data from 5 boreholes



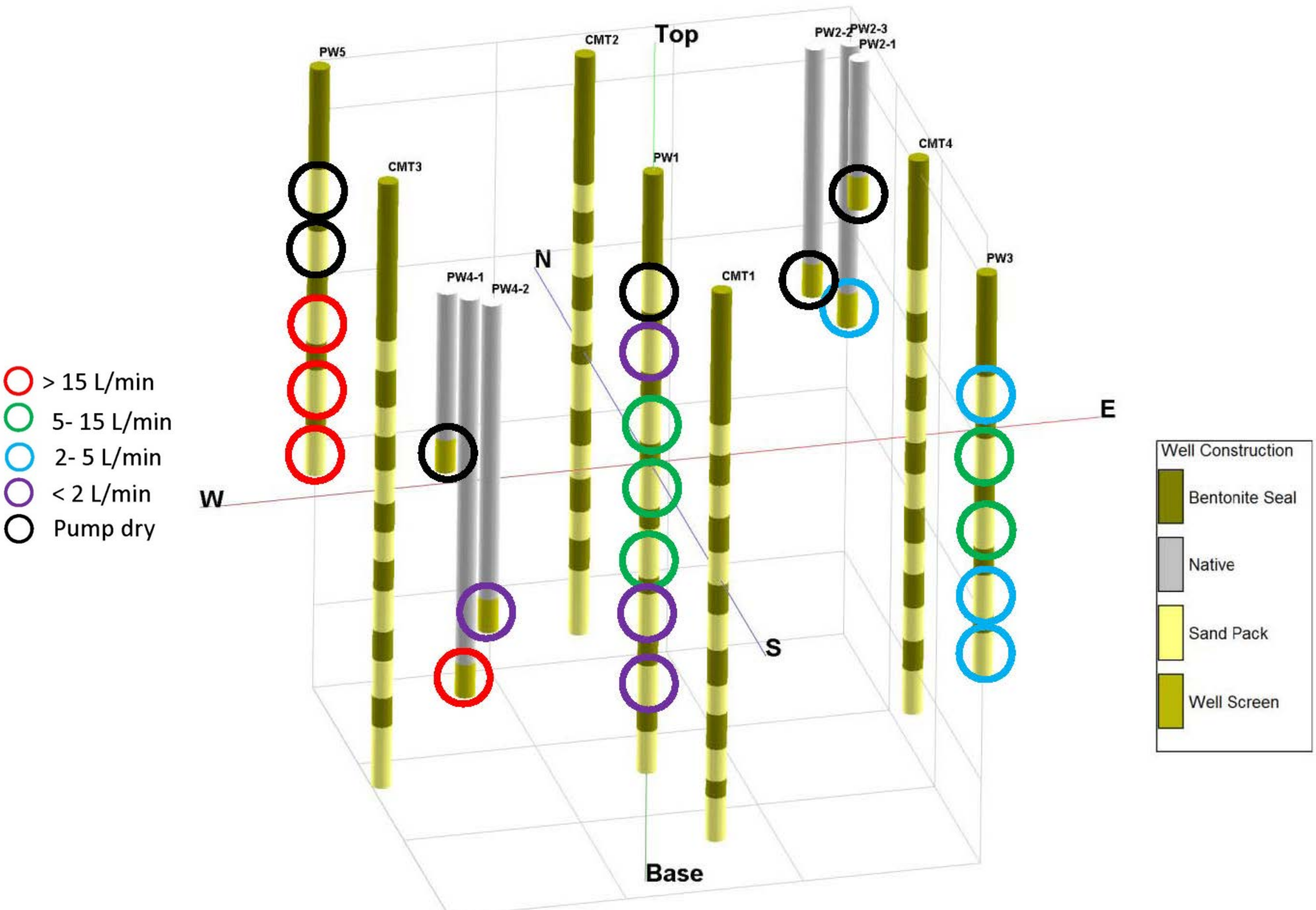
Characterization via grain size analyses, permeameter, slug and pumping tests

CMT's 7 zones each with pressure transducers



(*Alexander et al.*, 2011)

Well layout and pumping locations

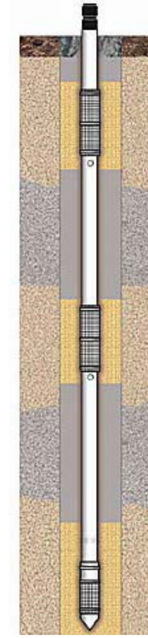


(Modified after *Berg and Illman*, 2011b)

Field equipment for hydraulic tomography

Packer system for pumping

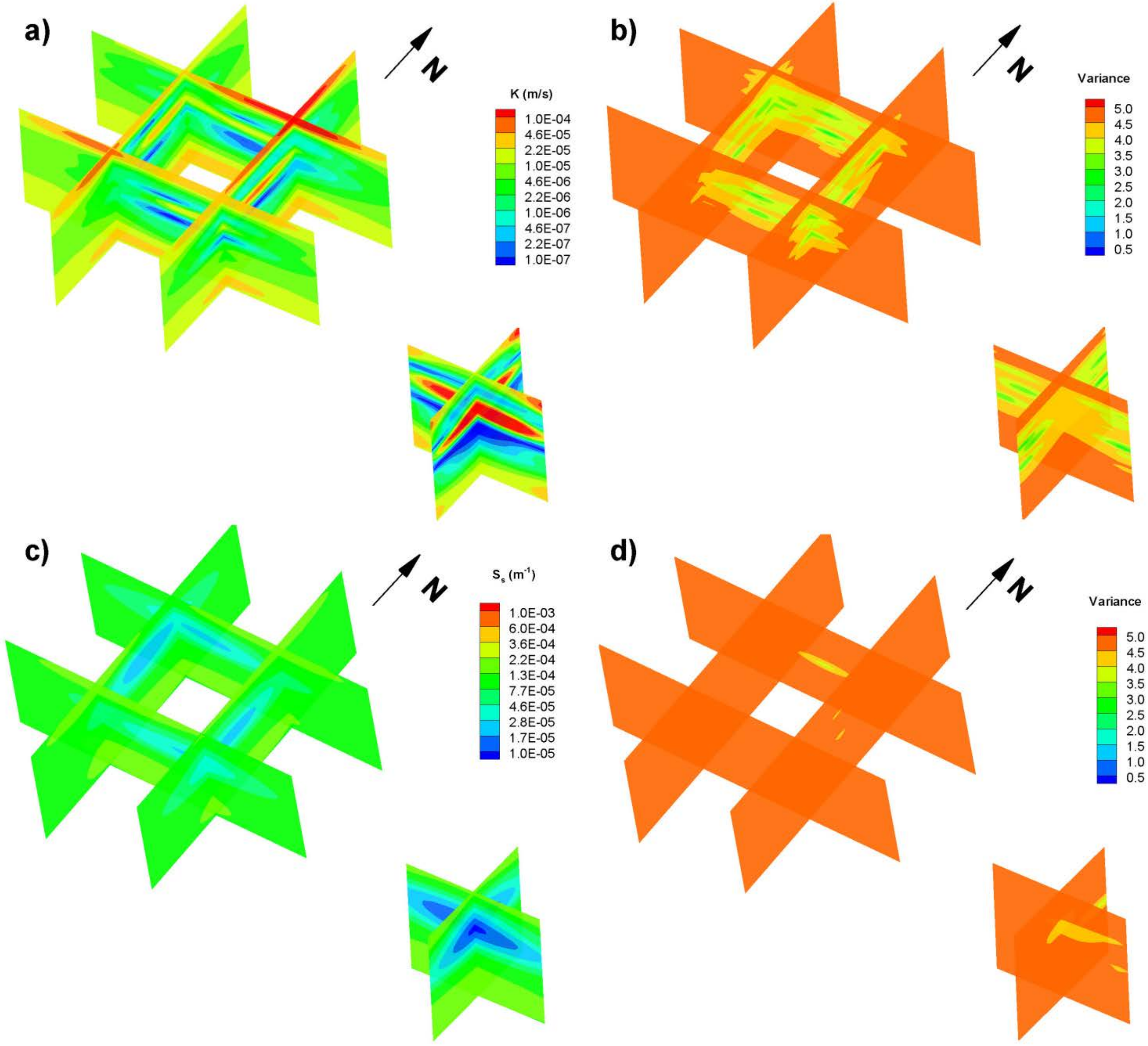
CMT system for monitoring



(*www.Solinst.com*)

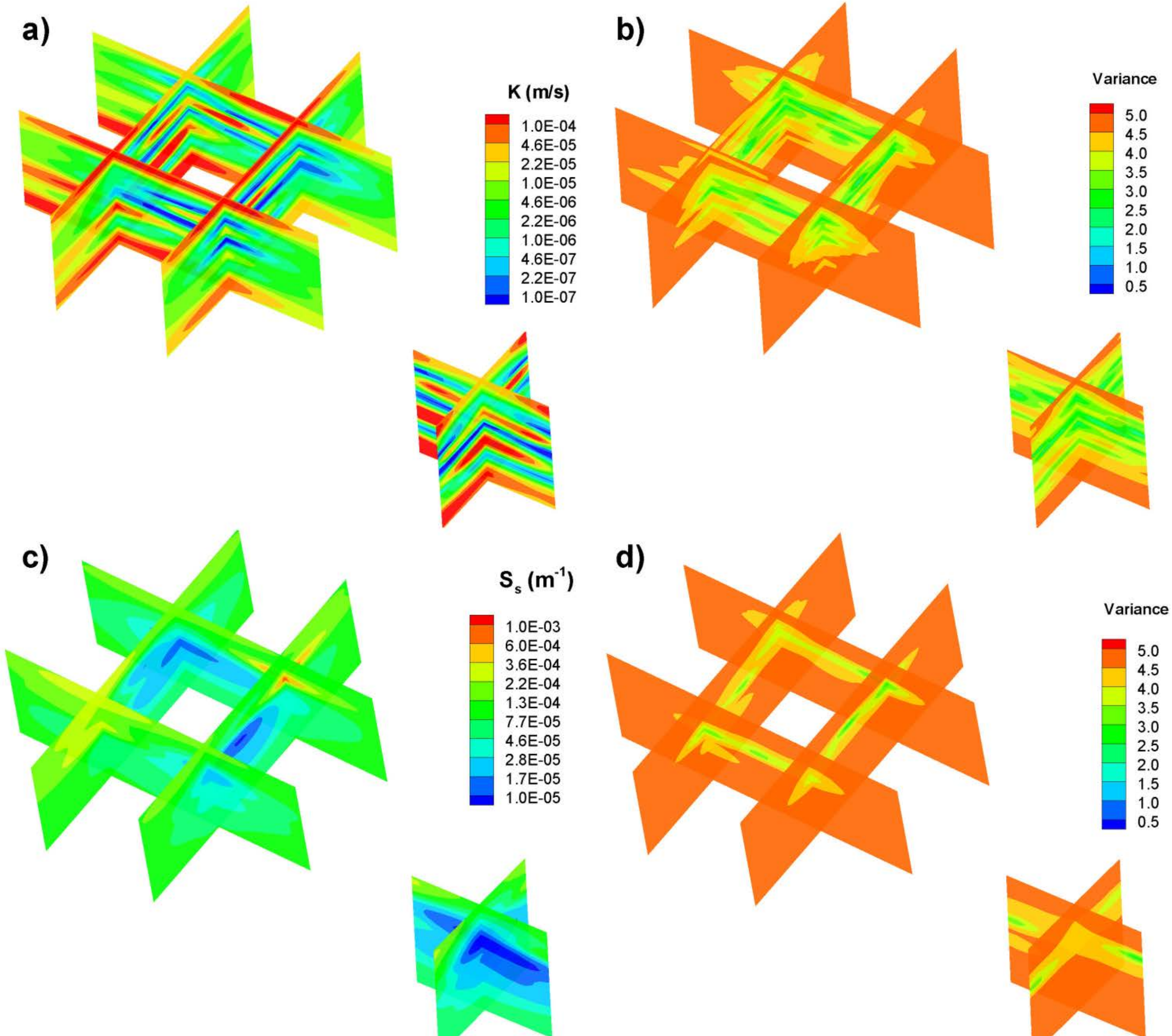
FLUTe system and nested wells for monitoring

Stochastic inverse modeling of 1 pumping test



(*Berg and Illman*, 2011b)

Transient hydraulic tomography analysis of 4 pumping tests



(*Berg and Illman*, 2011b)

Lessons learned

- Stochastic inverse modeling of single pumping tests gives limited information on heterogeneity (**uncertainty higher**);
- Hydraulic tomography integrates multiple pumping test data and hence provides more details to the aquifer (**uncertainty lower**);
- Uncertainty is lower (**greater confidence in parameter estimates**) because more data has been utilized in the analysis.

- Question:
  - Does hydraulic tomography also work in fractured rocks?

Hydraulic tomography analysis of kilometer-scale cross-hole interference tests in fractured rocks

University of Waterloo

Tono Geoscience Center

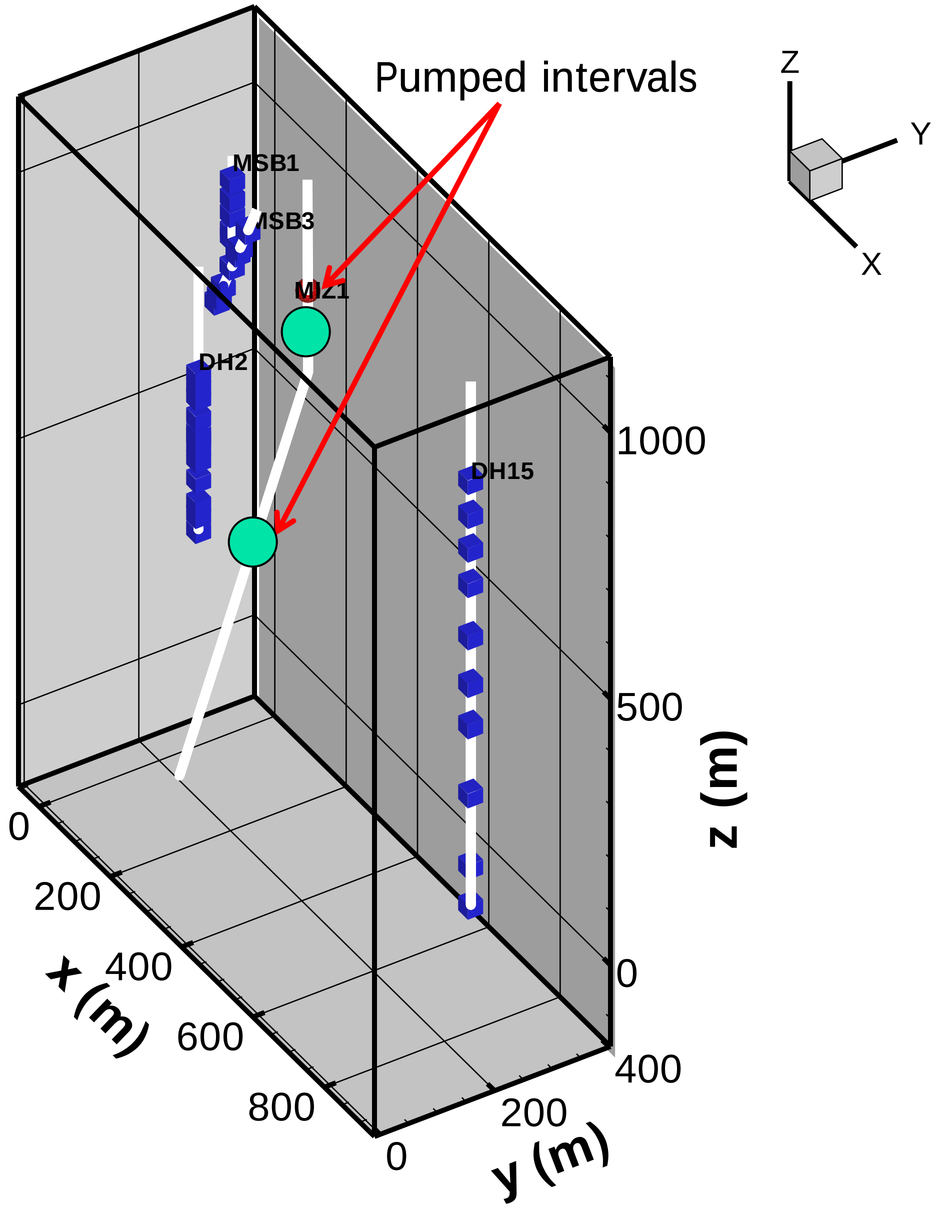
Mizunami Underground Research Laboratory (crystalline rock)

mbgl: meter below ground level

3D perspective view of boreholes and intervals used for cross-hole testing in fractured granite

2 pumping locations

34 observation intervals per test



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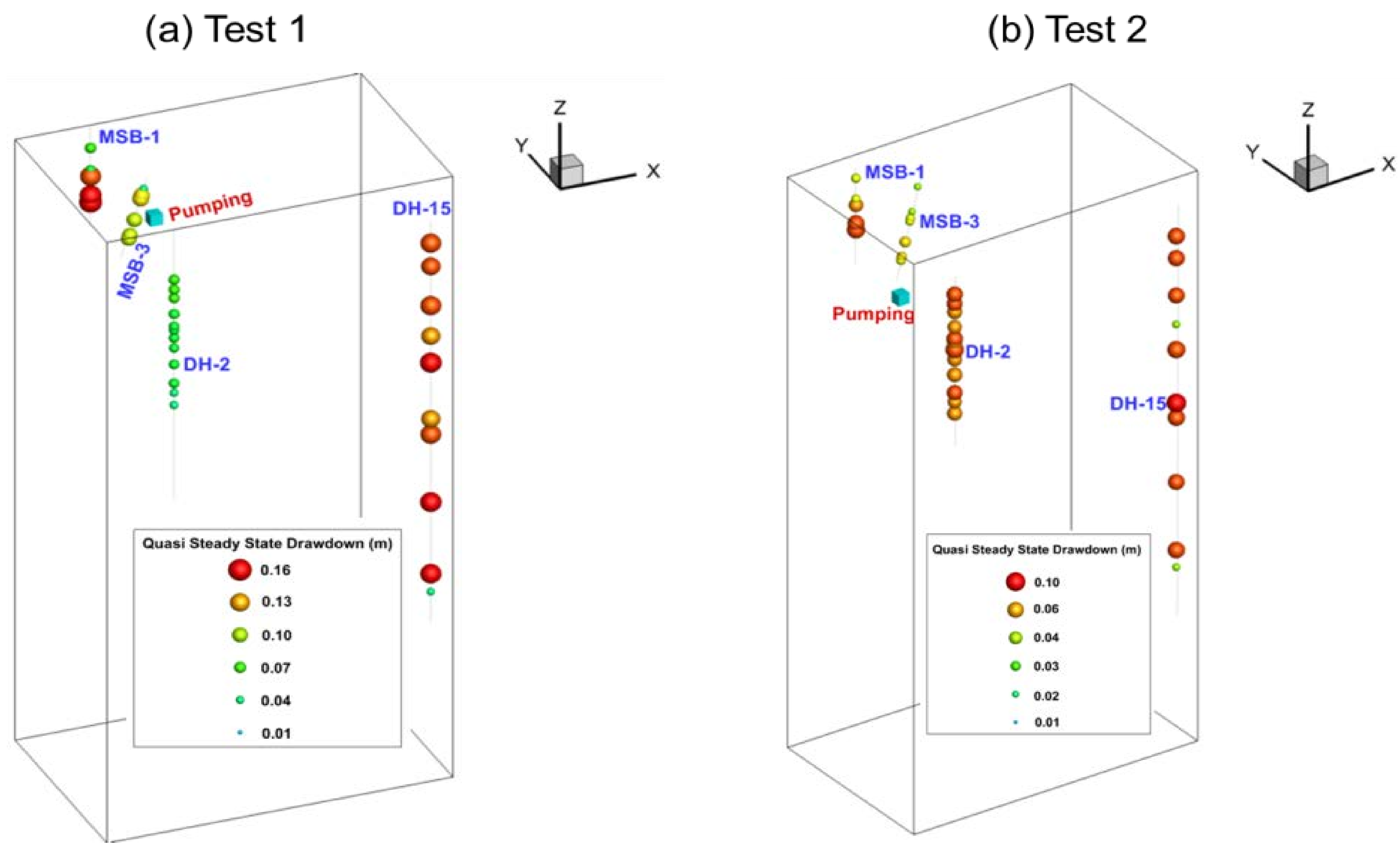
Test no	Test section Drilling depth (m)	Pumping rate （ L/min）	Pumping time （ day）	Total flow rate （ m3）
1	191.00-226.41	10.8	10.2	157.6
2	662.20-706.23	5.2	14.8	110.9

(*Illman et al.*, 2009)

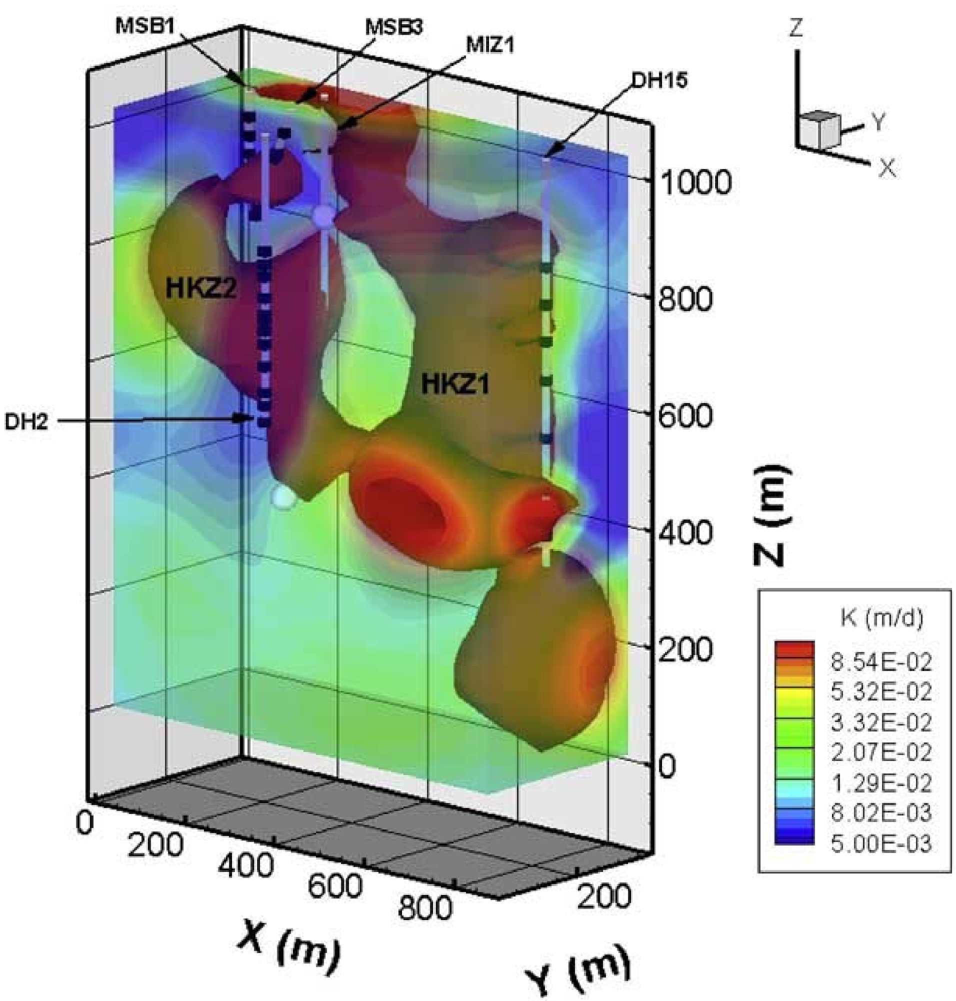
Drawdown responses due to cross-hole pumping tests that led to the hydraulic tomography study of *Illman et al*. (2009)



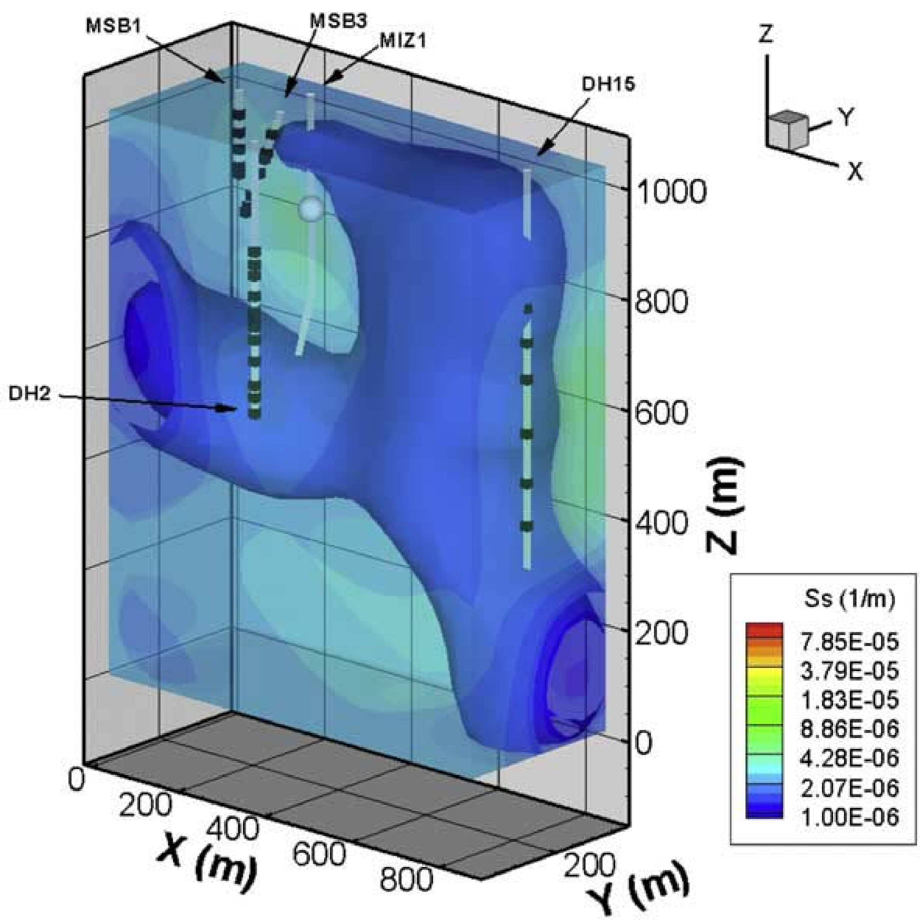
(*Zha et al*., submitted manuscript)

Hydraulic Tomography (HT) at the Mizunami site, Japan: Mapping of connectivity is possible because HT relies on pressure signals sent across rock

***K* tomogram (2 tests)**



S_s tomogram (2 tests)



(*Illman et al*., 2009)

Hydraulic Tomography as an alternative method for mapping faults (*Zha et al.*, submitted manuscript)

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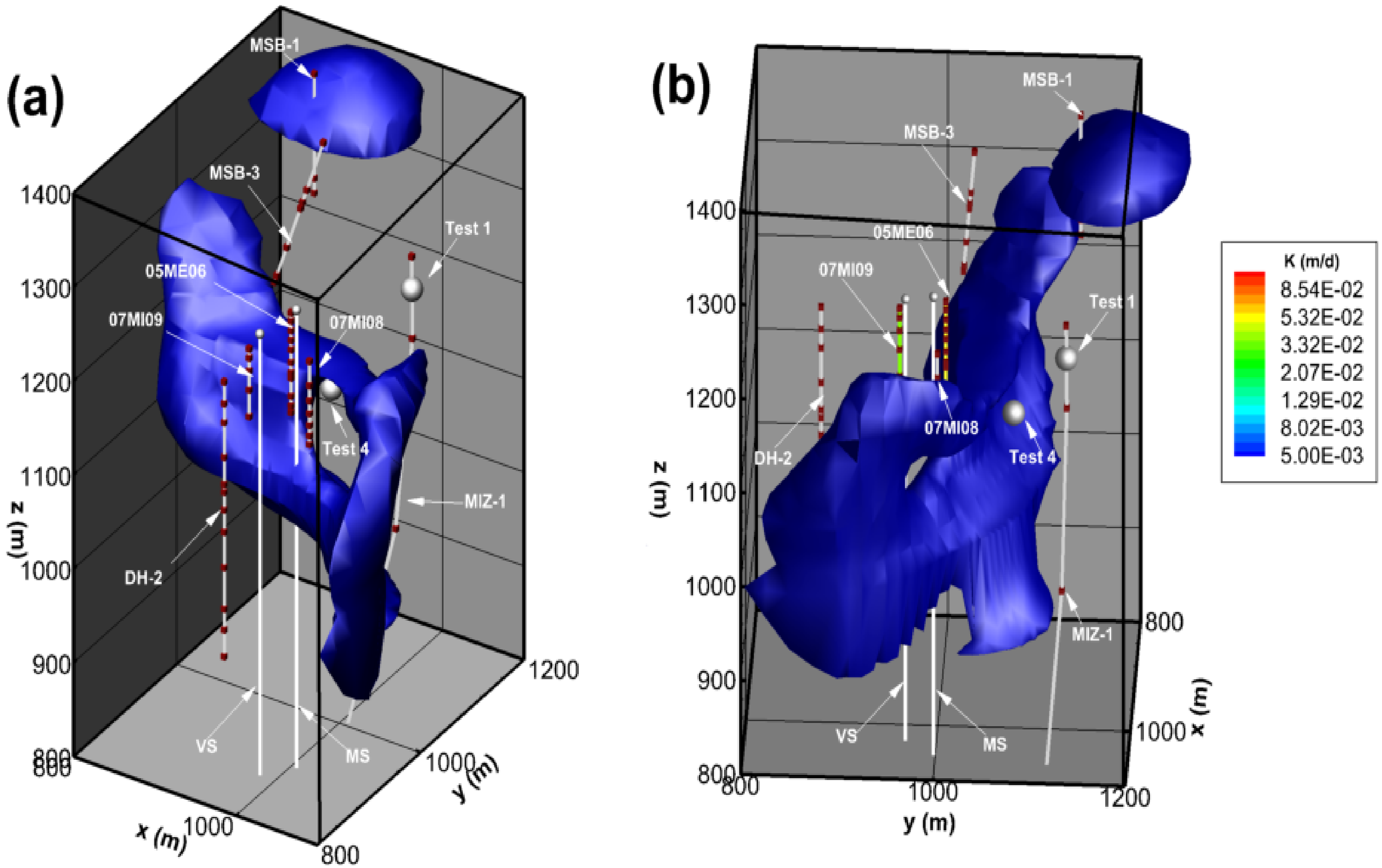
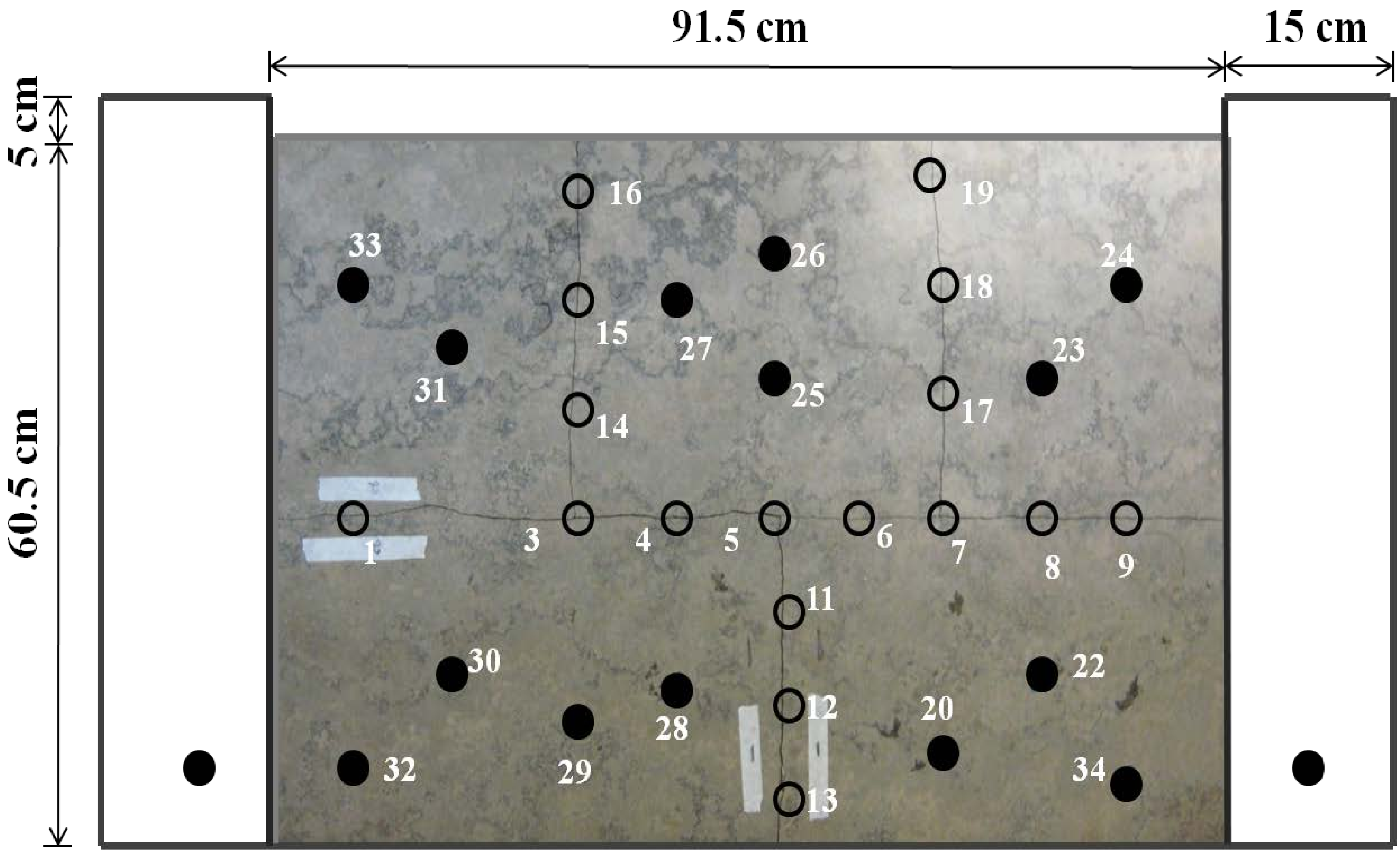
Updated *K* tomogram (4 tests)



The enlarged transient inversion results (*K* tomogram) using data from tests **1, 2, 3** and **4**. The spheres mark the location of the pumping wells (blue for test 1 and pink for test 4). (a, b) Isosurface value is *K* = 0.005 m/d.

But, can Hydraulic Tomography (HT) produce reliable maps of *K* and S_s heterogeneity?

Laboratory fractured dolostone block experiments

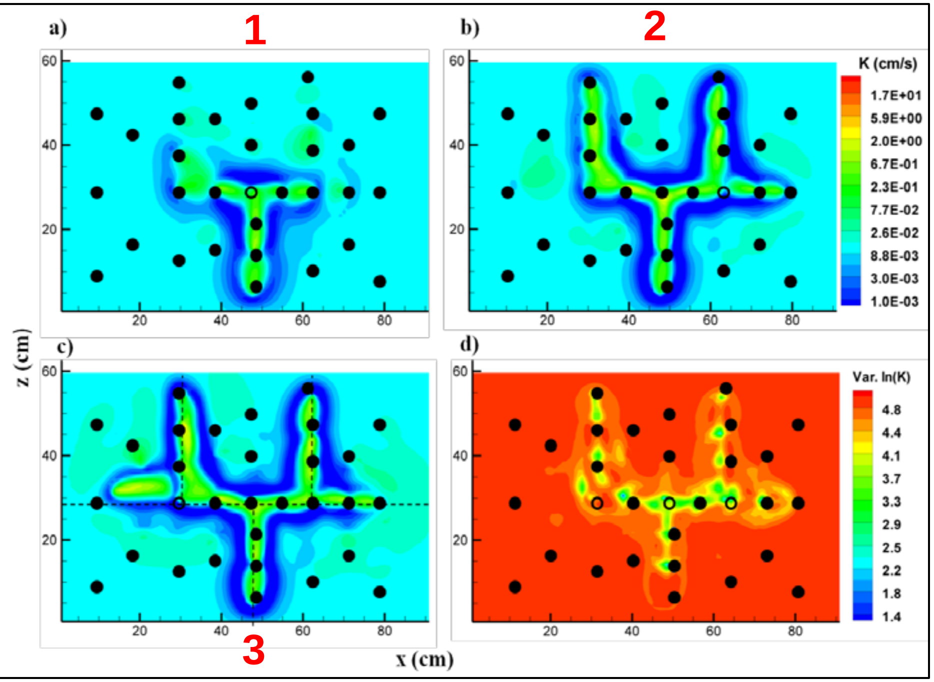


(*Sharmeen et al.*, 2012)

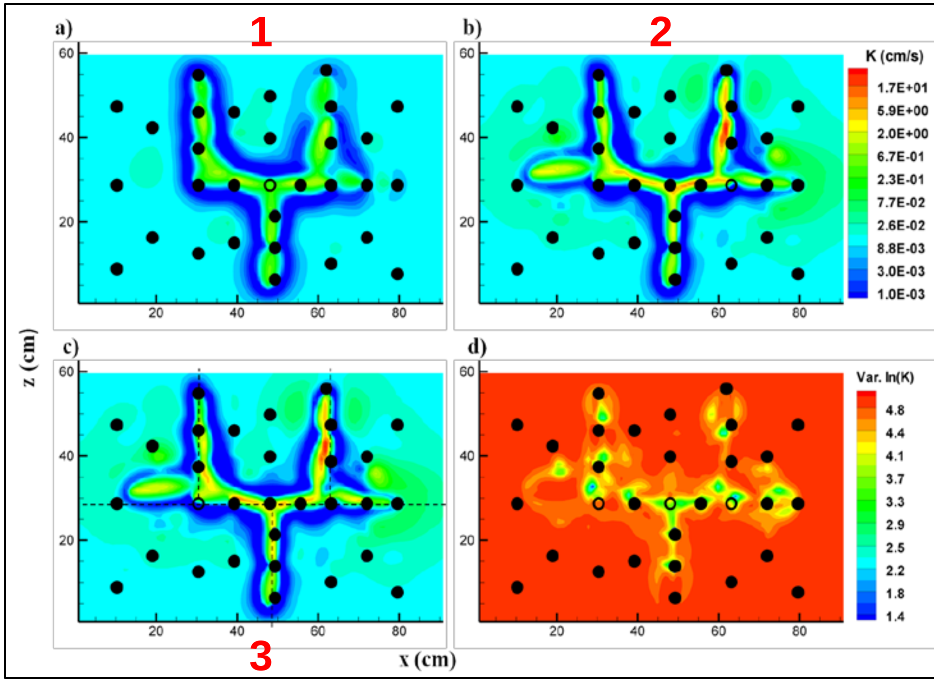
Hydraulic Tomography (HT) in fractured dolostone block in the lab

University of Waterloo

K tomogram from synthetic data (3 tests)



K tomogram from real data (3 tests)

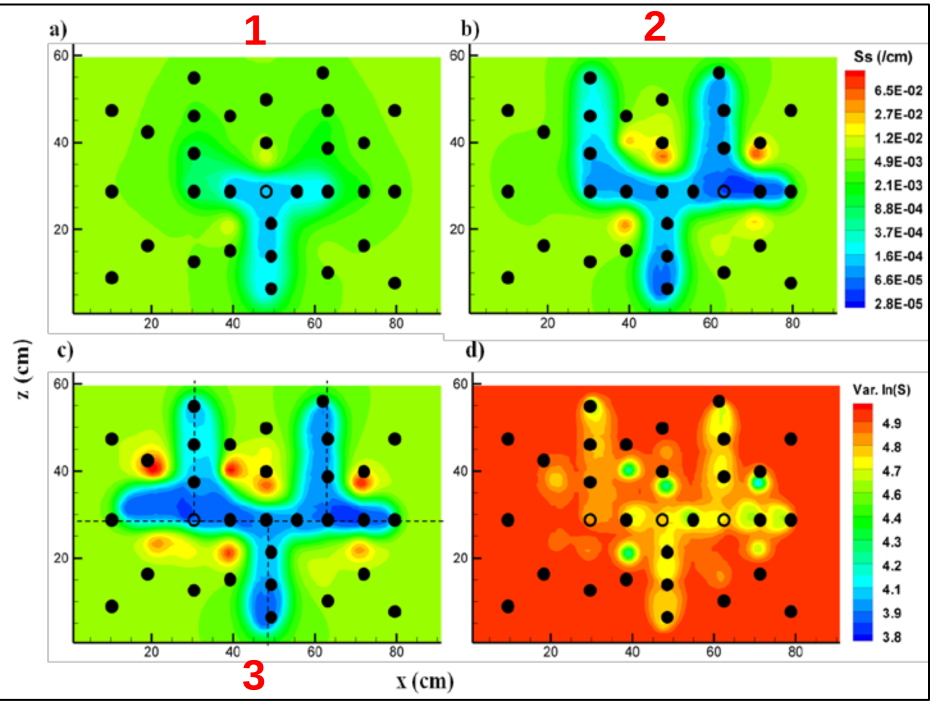


Note the accurate mapping of thin high *K* zones that delineate fractures in both synthetic and real inversion cases

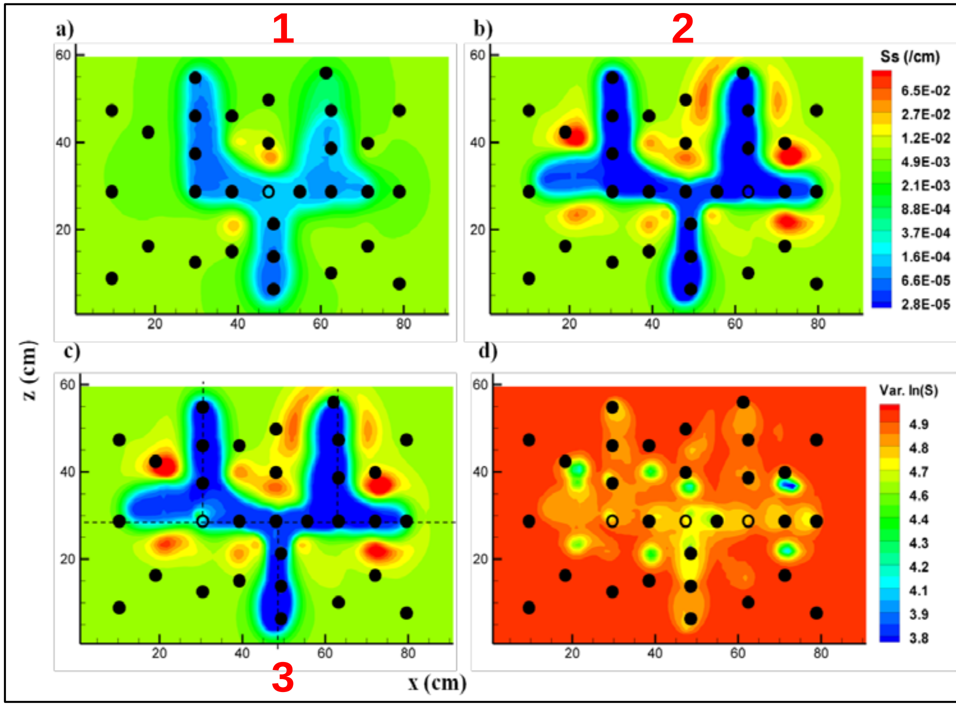
(*Sharmeen et al.*, 2012)

Hydraulic Tomography (HT) in fractured dolostone block in the lab

S_s tomogram from synthetic data (3 tests)



S_s tomogram from real data (3 tests)



Note the accurate mapping of thin low S_s zones that delineate fractures in both synthetic and real inversion cases

High K and low S_s zones = high diffusivity (α) zones

(*Sharmeen et al.*, 2012)

Summary

- Many different ways to characterize heterogeneity, but not easy to deal with heterogeneity;
- Inaccurate/biased hydraulic parameter estimates can affect dewatering operations, predictions of contaminant transport, remediation performance, and energy extraction;
- Hydraulic Tomography appears very promising in mapping K and S_s heterogeneity in both unconsolidated fractured rocks; provides uncertainty estimates;
  - Why? It relies on multiple pumping tests which gives direct information on heterogeneity and connectivity
  - Resolution depends on density of monitoring devices; low resolution can still provide more accurate/less biased effective parameter estimates;
  - “May” be improved with integration of other data
    - e.g., small scale hydraulic tests, geological, geophysical, tracer, temperature data.

Questions?

Further details can be found in *Illman, GW,* 52(5), 659-684, 2014

Groundwater

Issue Paper/

Hydraulic Tomography Offers Improved Imaging of Heterogeneity in Fractured Rocks

by Walter A. Illman

Abstract

Fractured rocks have presented formidable challenges for accurately predicting groundwater flow and contaminant transport. This is mainly due to our difficulty in mapping the fracture-rock matrix system, their hydraulic properties and connectivity at resolutions that are meaningful for groundwater modeling. Over the last several decades, considerable effort has gone into creating maps of subsurface heterogeneity in hydraulic conductivity (K) and specific storage (S_s) of fractured rocks. Developed methods include kriging, stochastic simulation, stochastic inverse modeling, and hydraulic tomography. In this article, I review the evolution of various heterogeneity mapping approaches and contend that hydraulic tomography, a recently developed aquifer characterization technique for unconsolidated deposits, is also a promising approach in yielding robust maps (or tomograms) of K and S_s heterogeneity for fractured rocks. While hydraulic tomography has recently been shown to be a robust technique, the resolution of the K and S_s tomograms mainly depends on the density of pumping and monitoring locations and the quality of data. The resolution will be improved through the development of new devices for higher density monitoring of pressure responses at discrete intervals in boreholes and potentially through the integration of other data from single-hole tests, borehole flowmeter profiling, and tracer tests. Other data from temperature and geophysical surveys as well as geological investigations may improve the accuracy of the maps, but more research is needed. Technological advances will undoubtedly lead to more accurate maps. However, more effort should go into evaluating these maps so that one can gain more confidence in their reliability.