Oak Ridge *IFRC*

Quantification of Plume-Scale Flow Architecture and Recharge Processes

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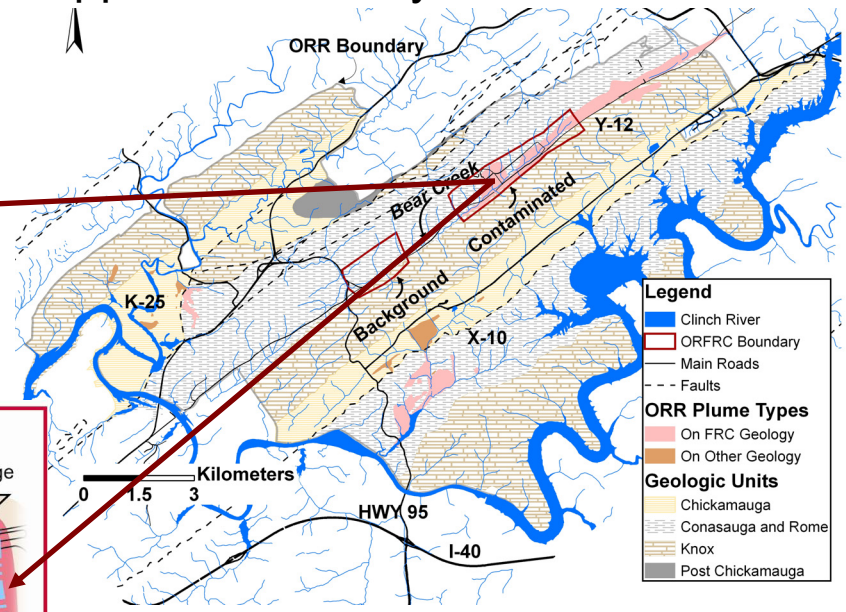
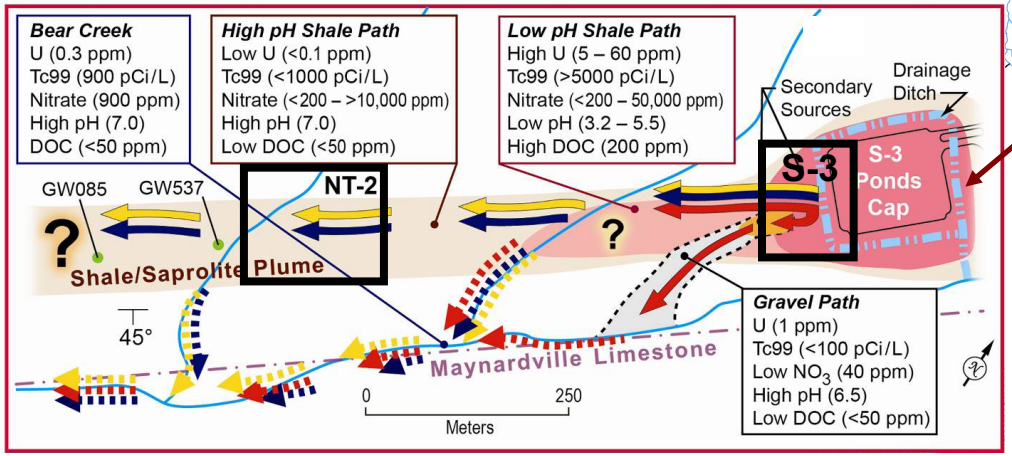
OUTLINE

1. **Quantification of Flow Architecture** at the Plume Scale using hydrogeophysical approaches
   - Challenges, Observations, Developed Approach and Results
2. **Recharge Process Monitoring** using Hydrogeochemical and Geophysical Methods
   - Motivation, New Methods, Datasets, Approaches, Early results

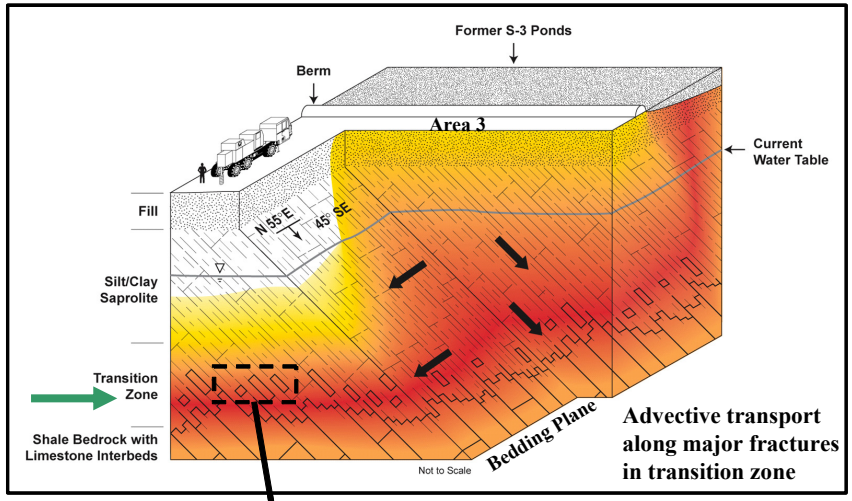


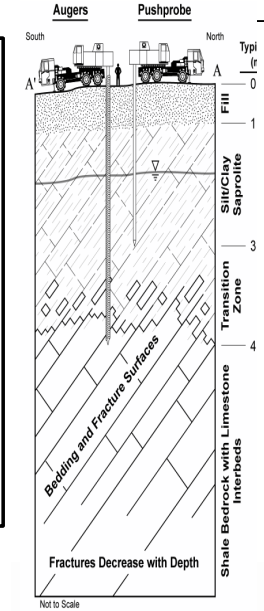


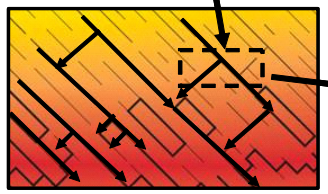
Part 1: Delineating Heterogeneity and Pathways

CHALLENGES:

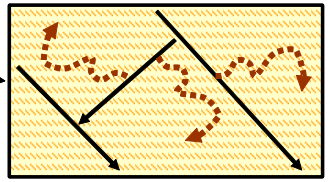
- Multiple Scales of Heterogeneity at ORNL IFRC
- Typical trade-offs between spatial coverage and resolution



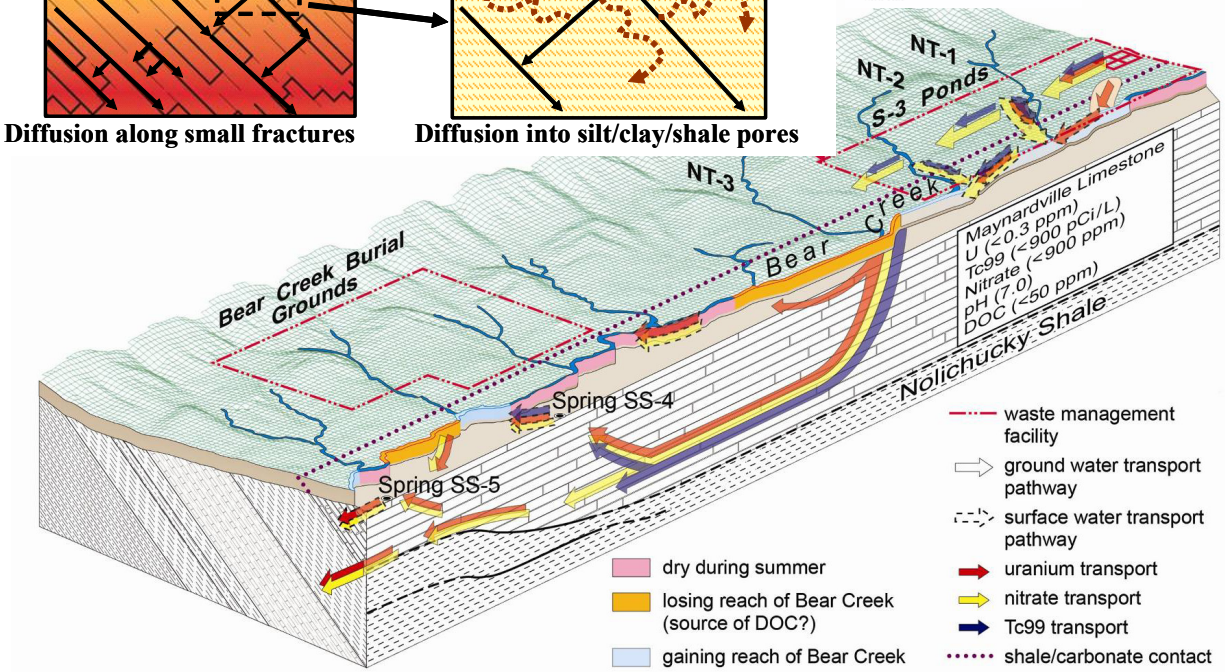




Diffusion along small fractures



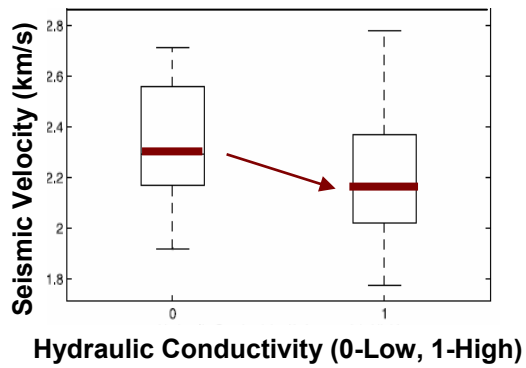
Diffusion into silt/clay/shale pores

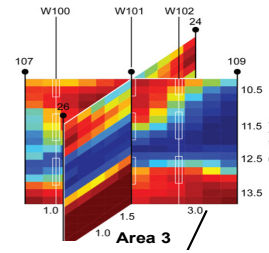


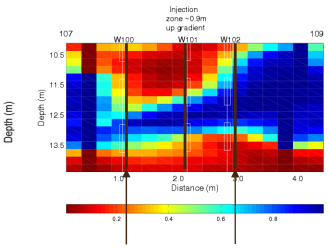
Previous Geophysical Characterization at ORNL provides motivation for Current Efforts

Local scale (Area 3).

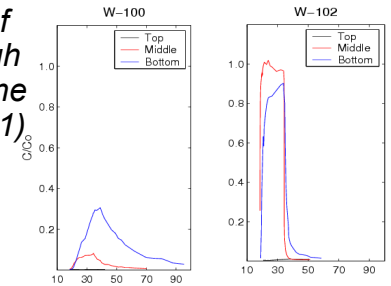
- **Low seismic tomographic velocity** indicative of high hydraulic conductivity fracture zones.
- Method developed to jointly invert wellbore flowmeter and seismic tomographic travel times in the **estimate of fracture zonation** (Chen et al., WRR, 2006)





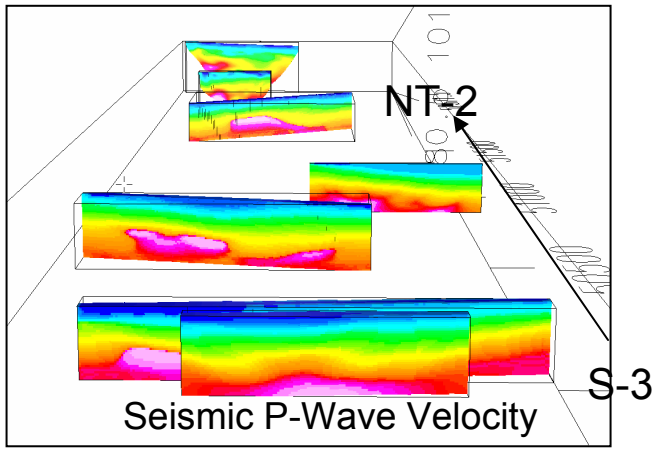


Probability of being in a high K fracture Zone (red=0, blue=1)



Watershed Scale

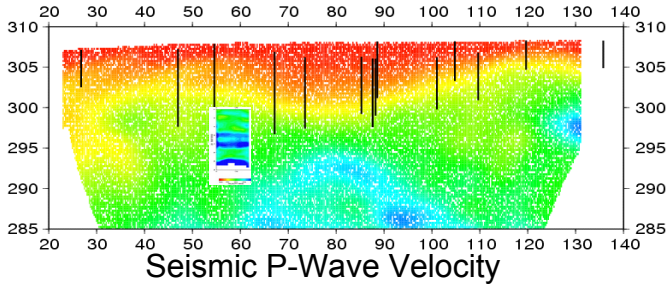
- **Surface seismic refraction** datasets collected perpendicular to and along the plume axis have revealed the presence of a laterally continuous low velocity zone.



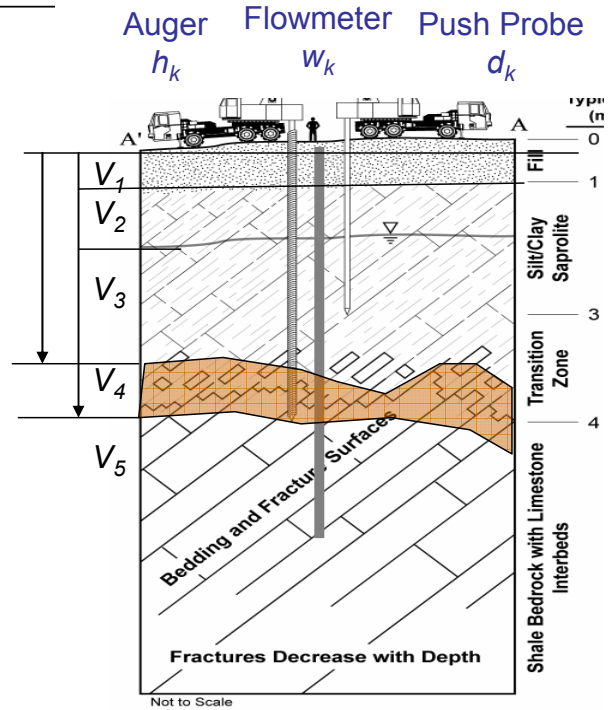
Can we jointly honor multi-scale relevant data in the quantification of major flowpaths?

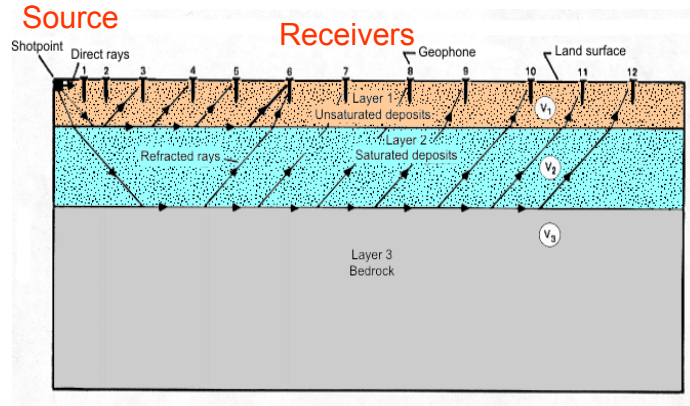
Multi-Scale

- Comparison of wellbore, crosshole, and surface geophyscial datasets suggest that multi-scale datasets provide information about **heterogeneity**.



Joint Inversion Approach

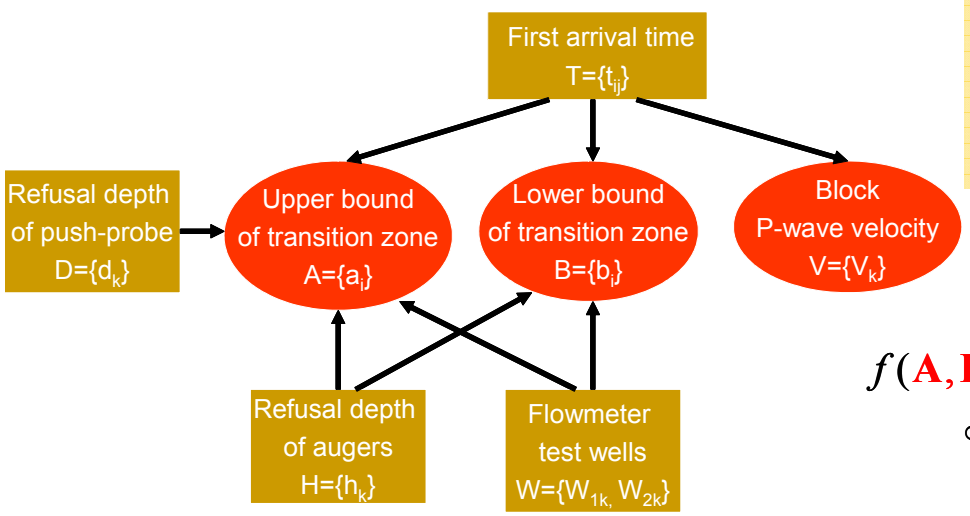




(From Maine Geological Survey webpage)

A 'one-step process':

- Jointly honors relevant datasets and prior knowledge in inversion procedure.
- Provides architecture estimates and associated uncertainties.
- Elastic 2D (rather than raypath) – works in traditionally 'difficult' environments (LVZ)



First arrival times

Depth constraints

$$f(\mathbf{A},\mathbf{B},\mathbf{V},\delta,\tau \mid \mathbf{T},\mathbf{W})$$

$$\propto f(\mathbf{T} \mid \mathbf{A},\mathbf{B},\mathbf{V},\delta,\tau) f(\mathbf{W} \mid \mathbf{A},\mathbf{B})$$

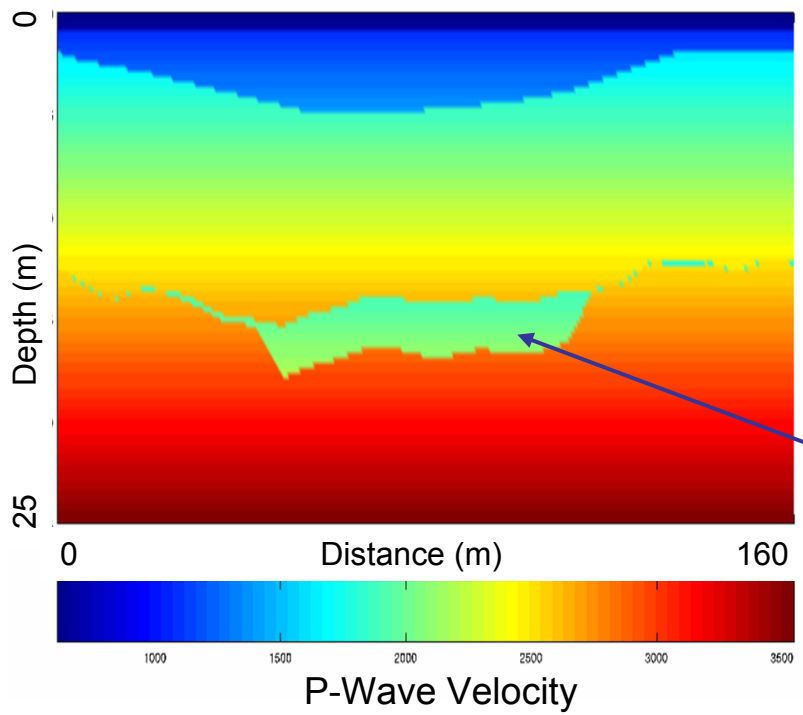
$$f(\mathbf{A},\mathbf{B}) f(\mathbf{V}) f(\delta) f(\tau)$$

Joint Inversion Example at S-3

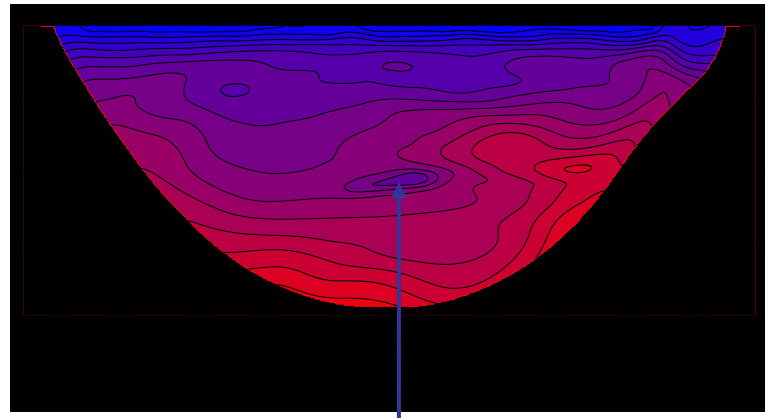
Comparison of Joint and Traditional Inversion Results near Source

Bayesian Joint Inversion

(only mean interface values shown)



Traditional inversion

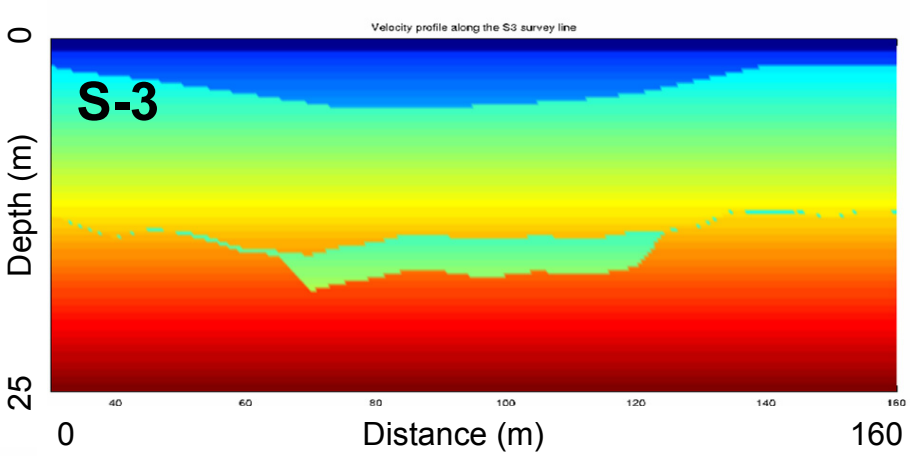


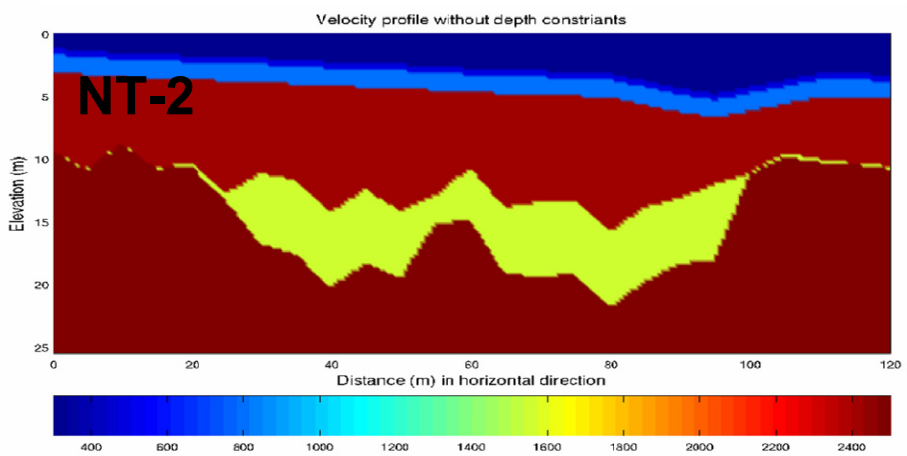
Low velocity zone

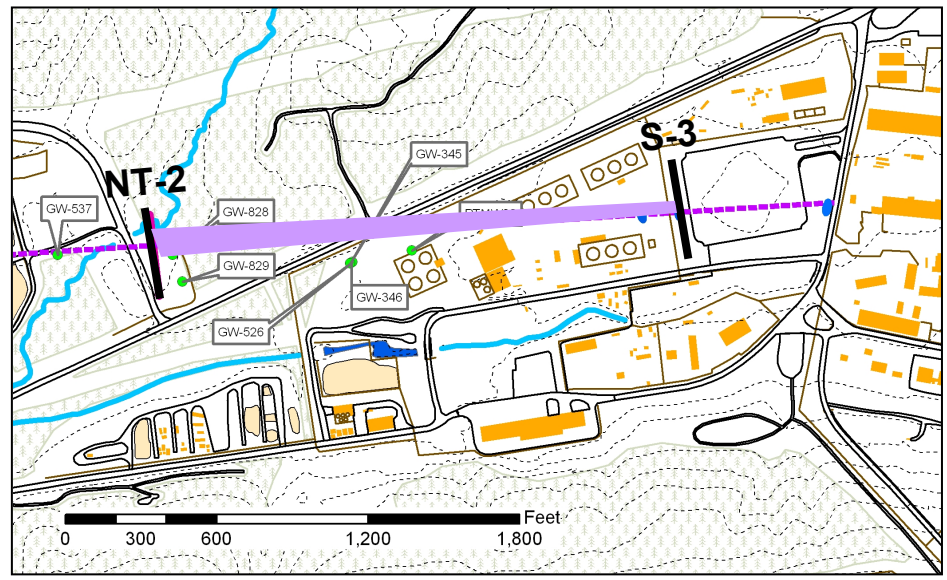
Synthetic studies (not shown) suggest Bayesian approach provides:

- Improved delineation of interfaces and Low Velocity Zone;
- Good quantification of interface depth uncertainties.

Quantifying Architecture of Low Velocity Zone from S-3 to NT-2







Differential weathering of competent dipping bedrock beneath saprolite?

Laterally Continuous?

Major flow pathway?

Drilling campaign planned for 2009.

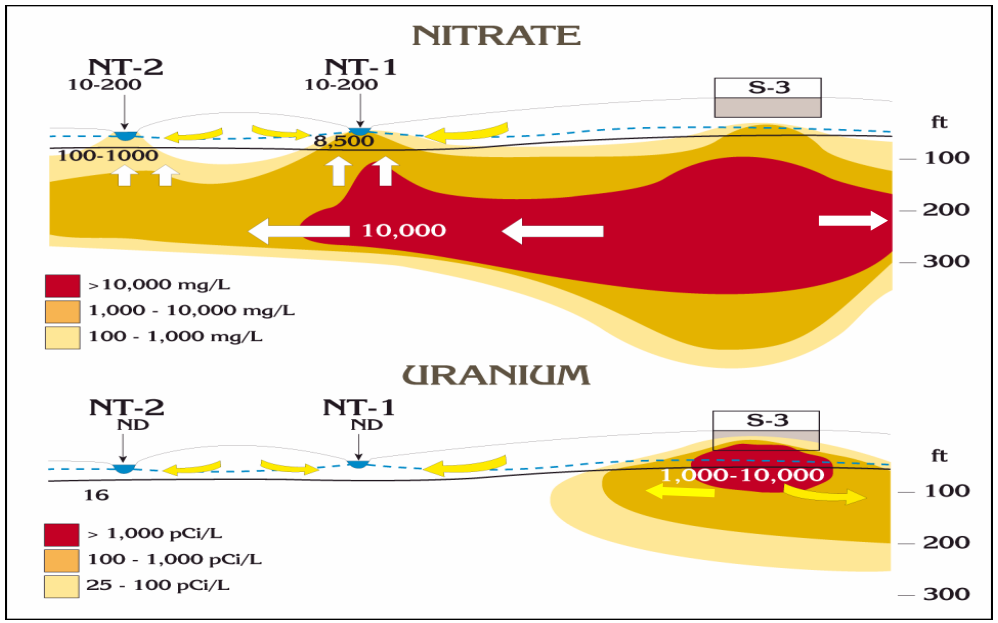
Developed method permits synchronous consideration of geophysical and other (i.e., wellbore) multi-scale measurements for quantitative architecture characterization

Chen et al., WRR, in development

Part 2: Monitoring Recharge Processes

- **Key Components**:
  - **Precipitation**
    - low ionic strength
    - high DO
    - pH~5.5
  - **Reactive system**
    - High ionic strength and low pH groundwater (especially near source)
    - Significant Al and Fe oxides
    - Variable mineralogy along different pathways (shale, gravel, carbonate)
    - Contaminants such as nitrate & U.
  - **Heterogeneous Hydrogeology**
    - Drainage ditch
    - Perched water
    - Matrix vs. fracture pathways
    - Role of antecedent conditions

- **Recharge creates large hydraulic and geochemical gradients that disrupt equilibrium**

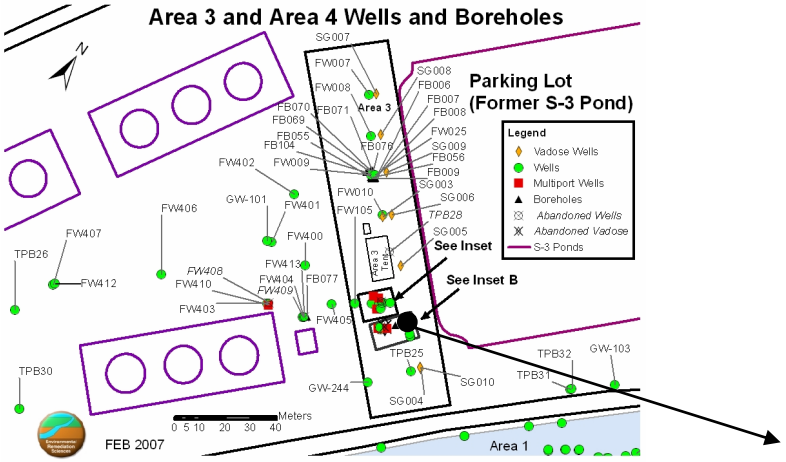


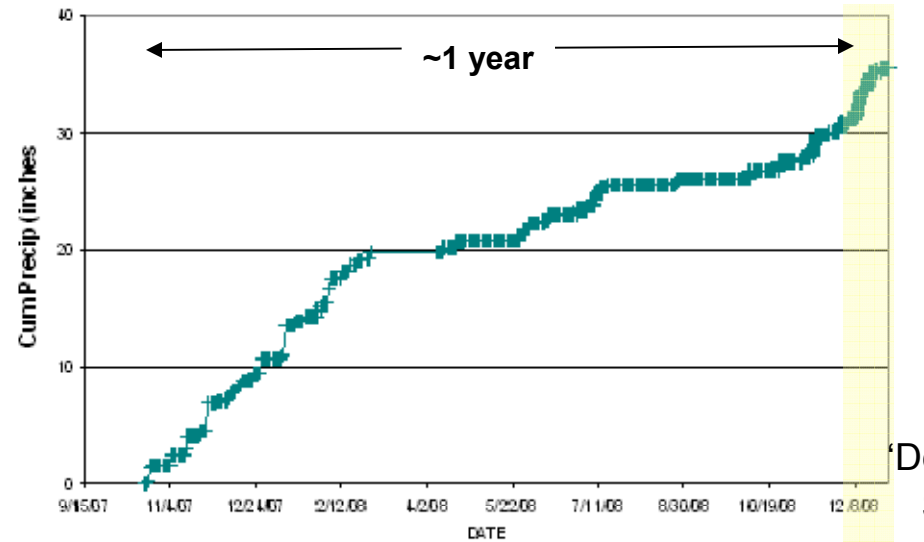
KEY QUESTIONS

- *Which recharge-related processes dominate at which locations in the watershed?*
- *How do these processes impact contaminant concentration and mobility?*
- *What is the time lag between recharge events and re-establishment of geochemical equilibrium?*
- *Can non-traditional methods be used to explore recharge processes across the plume?*

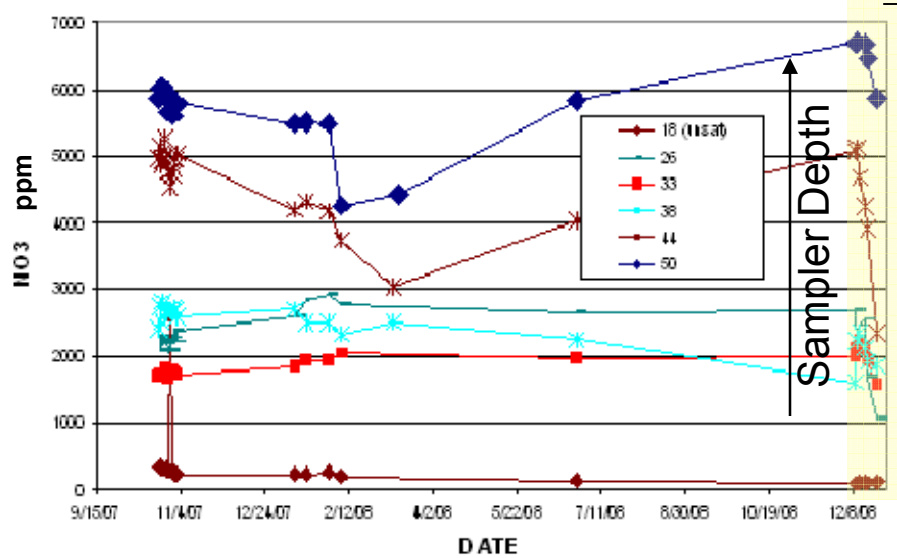
Monitoring Recharge Processes: Extensive wellbore dataset

*Cumulative (~Annual) precipitation & Nitrate in a **single well** near S-3 source:*





'December' Storms

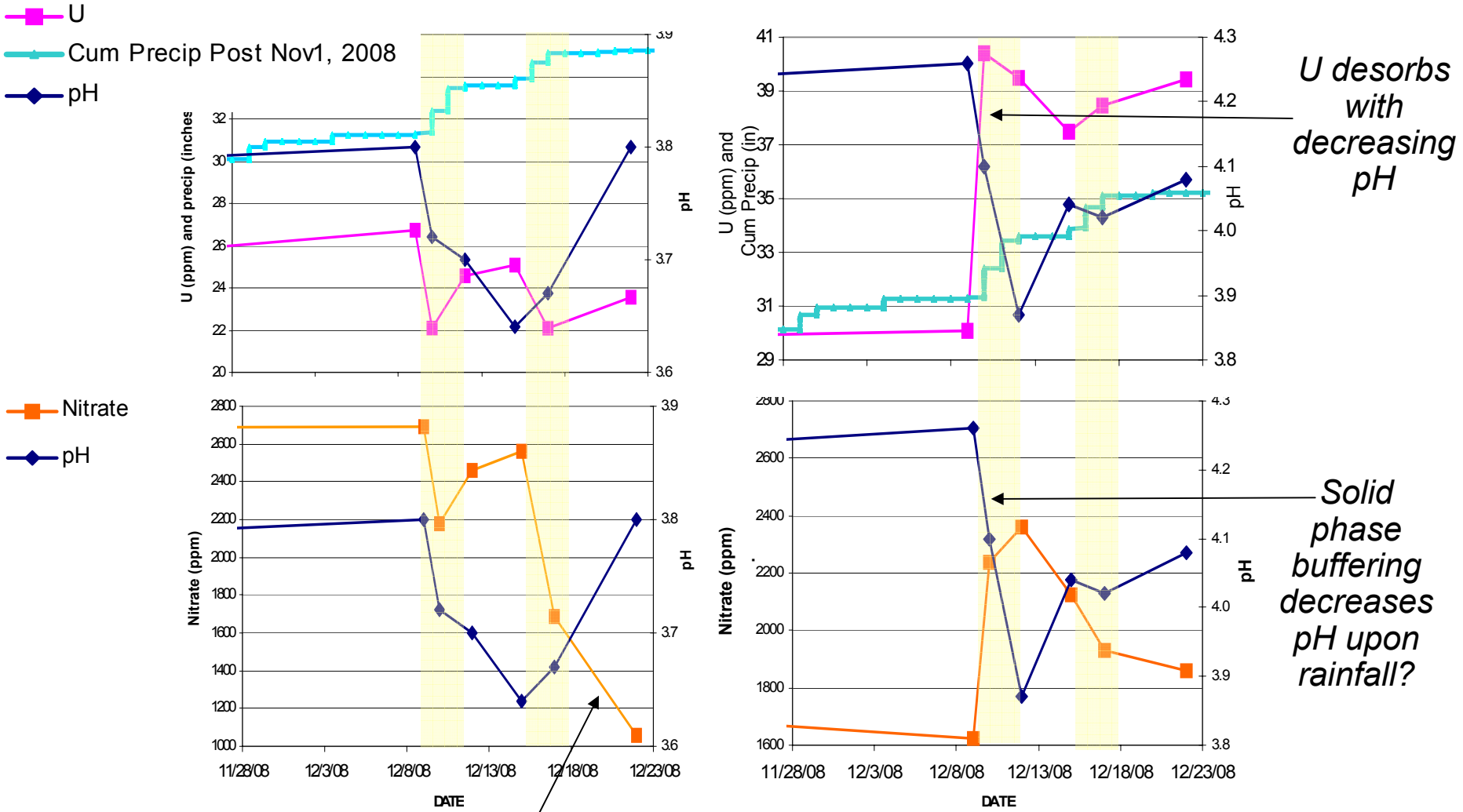


Investigate all key variables at all wells as function of:

- *Precipitation: Seasonal and episodic storm events*
- *Depth*
- *Heterogeneity*
- *Distance from Source*

Precipitation, pH, Nitrate and U Concentrations in FW120 (Near Source)

Shallow Groundwater (~7m BGS) **Deeper Groundwater** (~11m BGS)

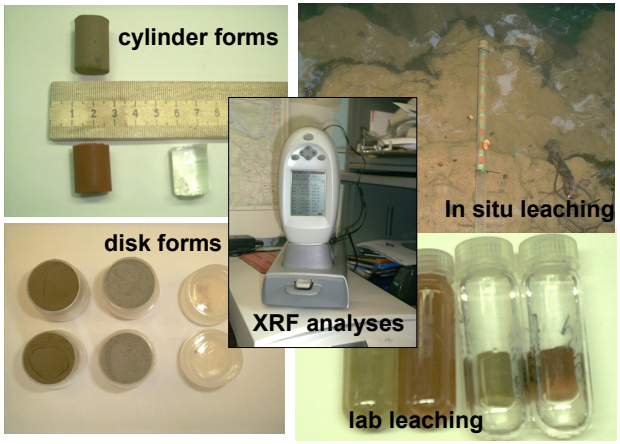


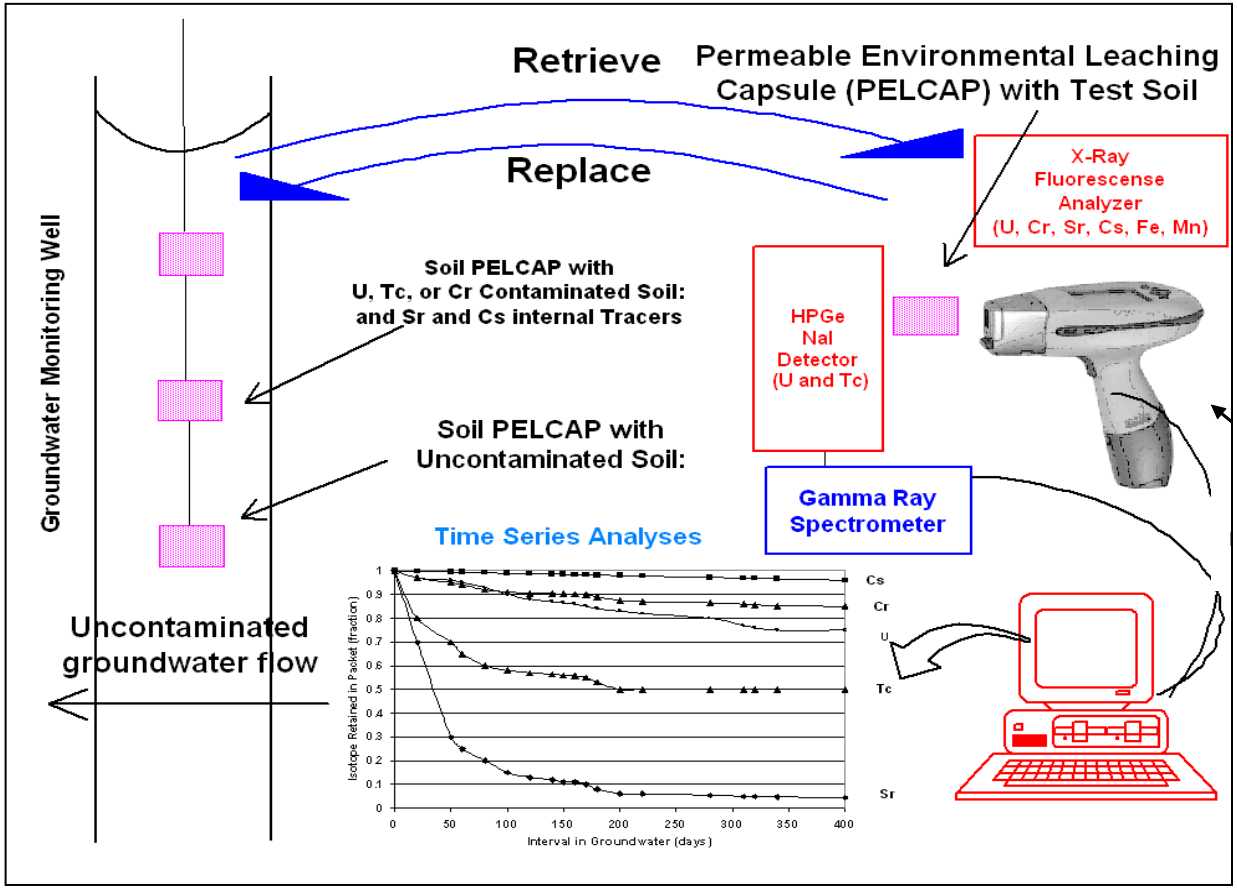
Eventual nitrate dilution in shallow groundwater due to rainfall?

Different Recharge-related Processes!

Permeable Environmental Leaching Capsules (PELCAPs)

Quantifying *In situ* Reactive Contaminant Behavior Across the Watershed



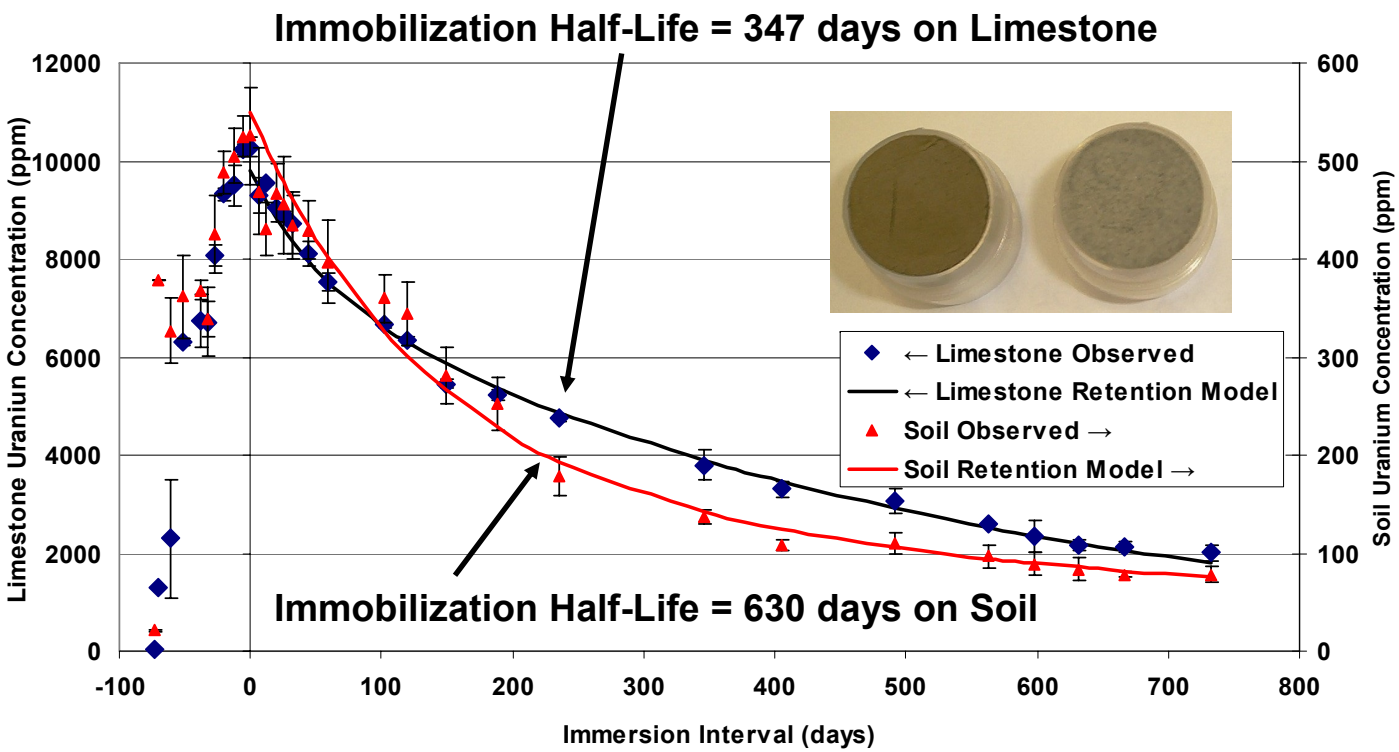


Brian Spalding

PROPERTIES

- Hydrogel-encapsulated soil samples are useful to follow in situ uptake and release of uranium by soil when immersed in groundwater.
- Polyacrylamide hydrogels are stable in situ for up to two years (and counting).
- No detectable interaction of uranium with hydrogel itself

Use of Pelcaps to explore U immobilization of different subsurface materials under 'Natural Attenuation' conditions (i.e. pH rebound/solubility of U)



- Uranium loading: limestone and soil pelcaps were placed in FW106
- Spring water used to study in-situ leaching (days>0 in above plot)
- Kinetic modeling performed to estimate leaching half lives and other parameters.
- ➢ *Using technology to compare long term performance of various remedial strategies (bioreduction w/ different amendments, natural attenuation, pH manipulation, phosphate addition, etc.)*

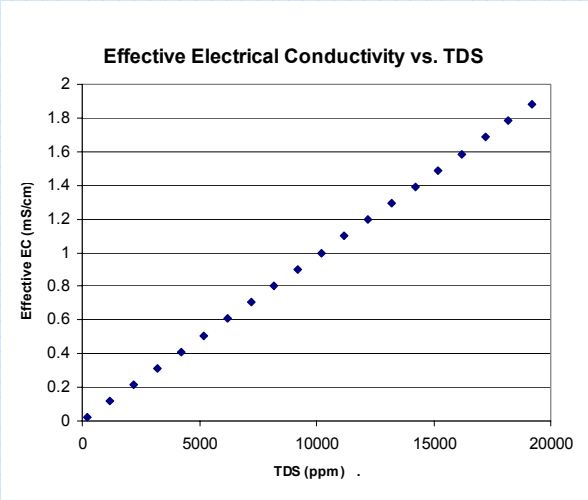
Geophysical Monitoring of Recharge Processes

- Geophysical responses to recharge processes.
- Development of novel monitoring methods.
- Joint incorporation of hydro-geochemical and geophysical datasets to test geophysical sensitivities and explore dynamic processes.
- Scaling of electrical response from log to crosshole to surface mode.

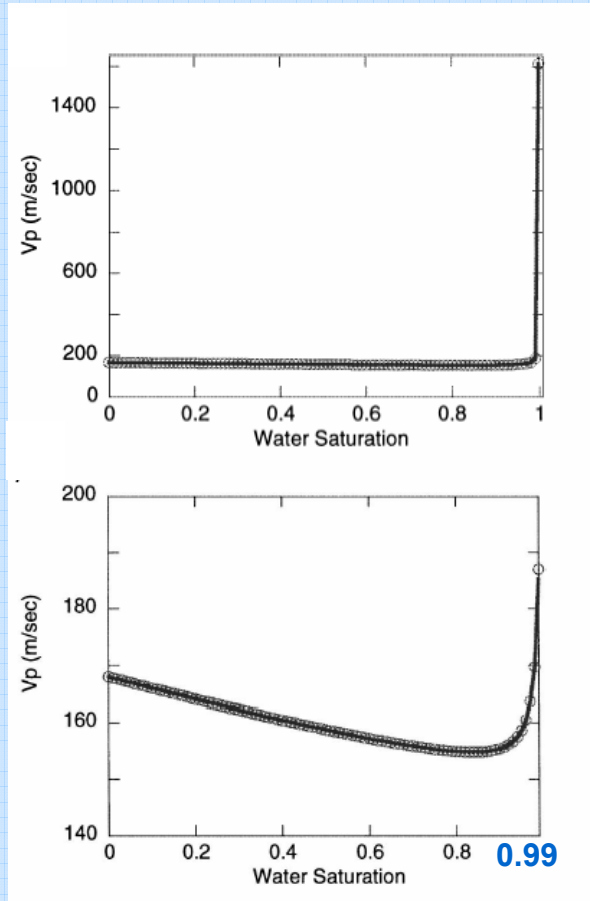
Petrophysical Relationships

Effective Electrical Conductivity increases as a function of increasing:

- TDS
- Saturation
- Porosity
- Surface Conduction
- Temperature



Seismic P-Wave Velocity



Biot-Gassman prediction for Vp changes as a function of water saturation (modified from Bachrach et al., 1988)

Time Lapse Seismic Refraction Tomography (TLSRT)

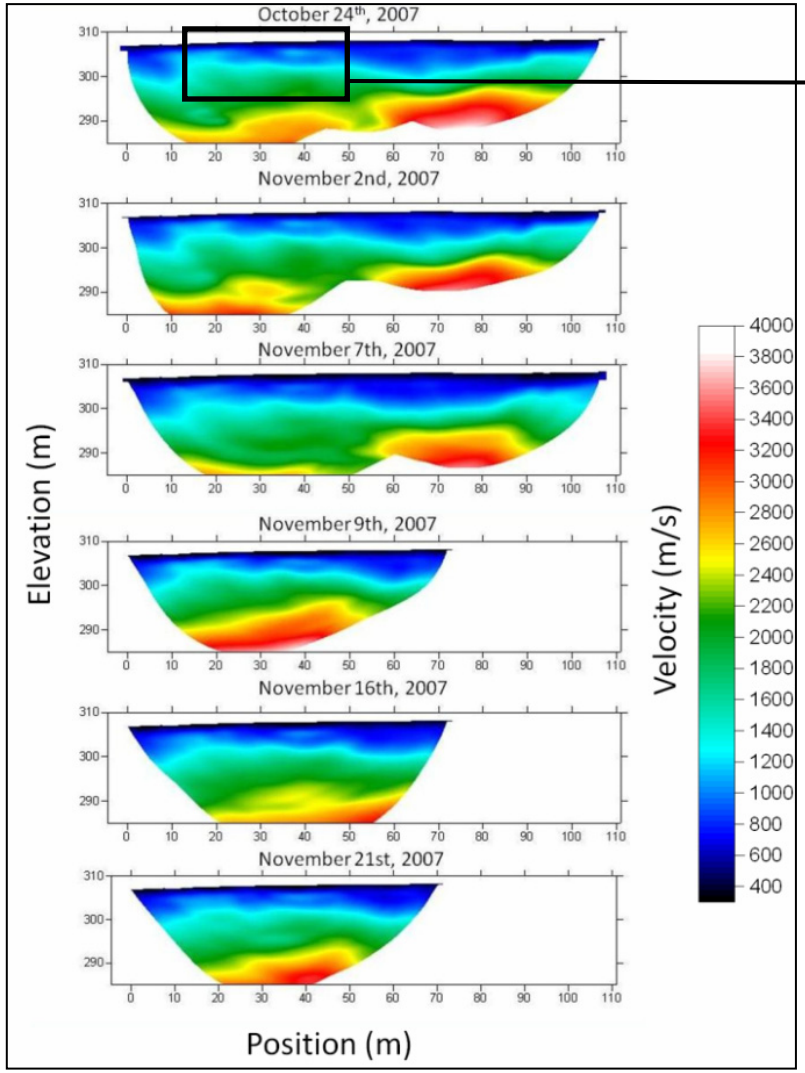
35 Campaigns: seismic refraction profile and 4 wellbores

- **Seismic velocity changes as a function of perched water saturation**
- **Changes in seismic beyond site-specific established 'error'.**

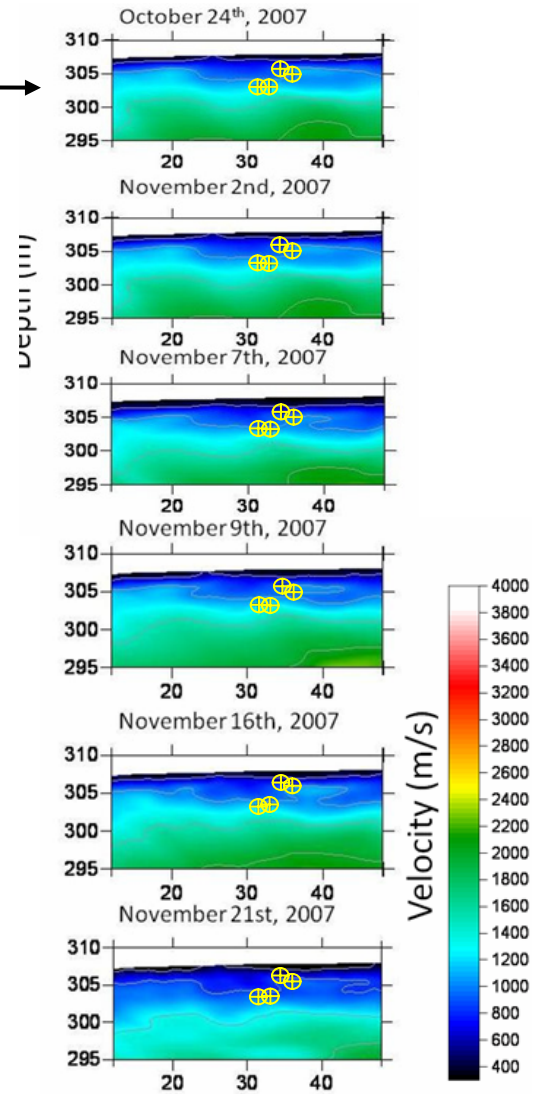
New method for tracking perched water table responses to recharge

Gaines et al., in submission, 2009

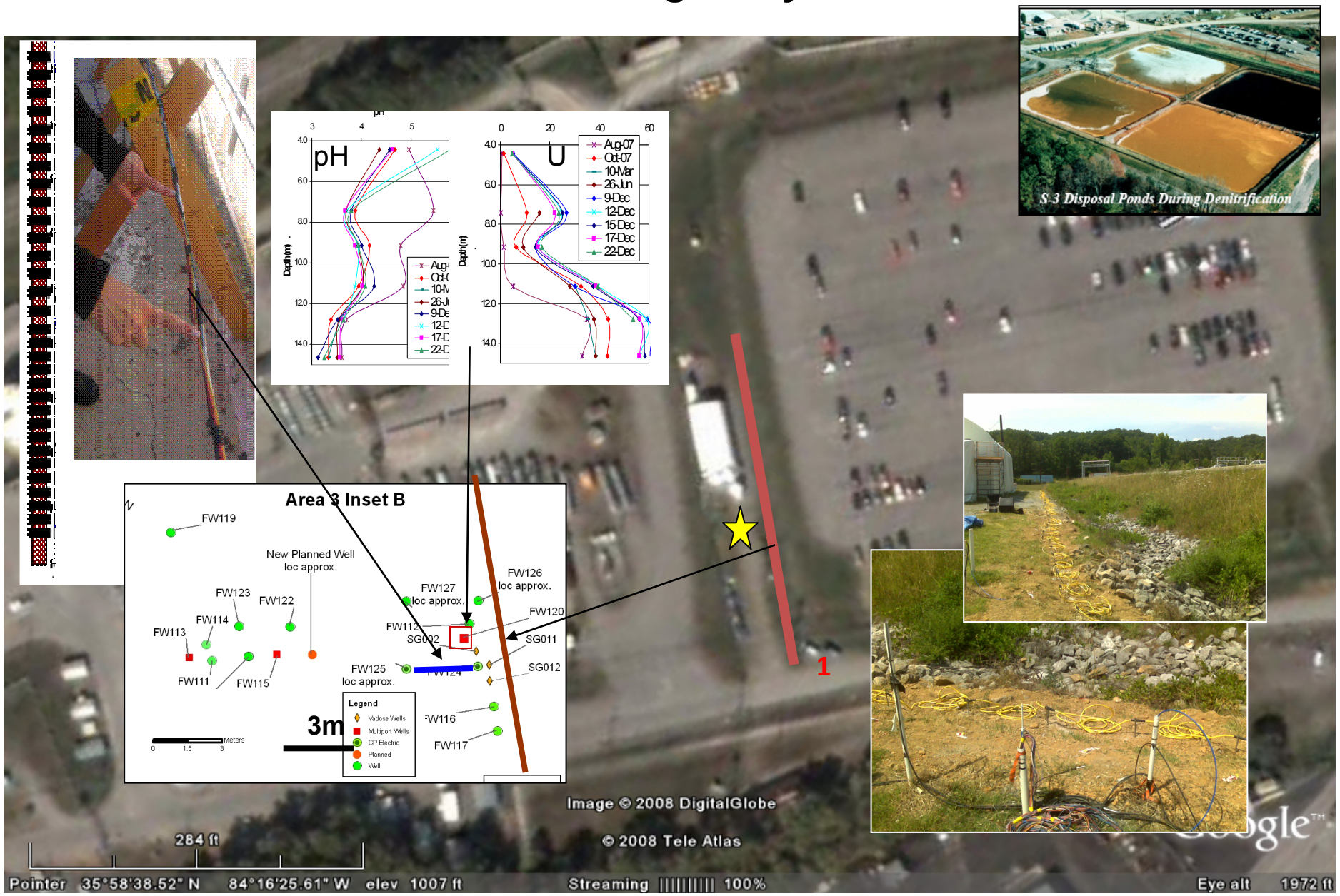
Inverted Seismic Refraction Profile



Detail, showing perched water locations

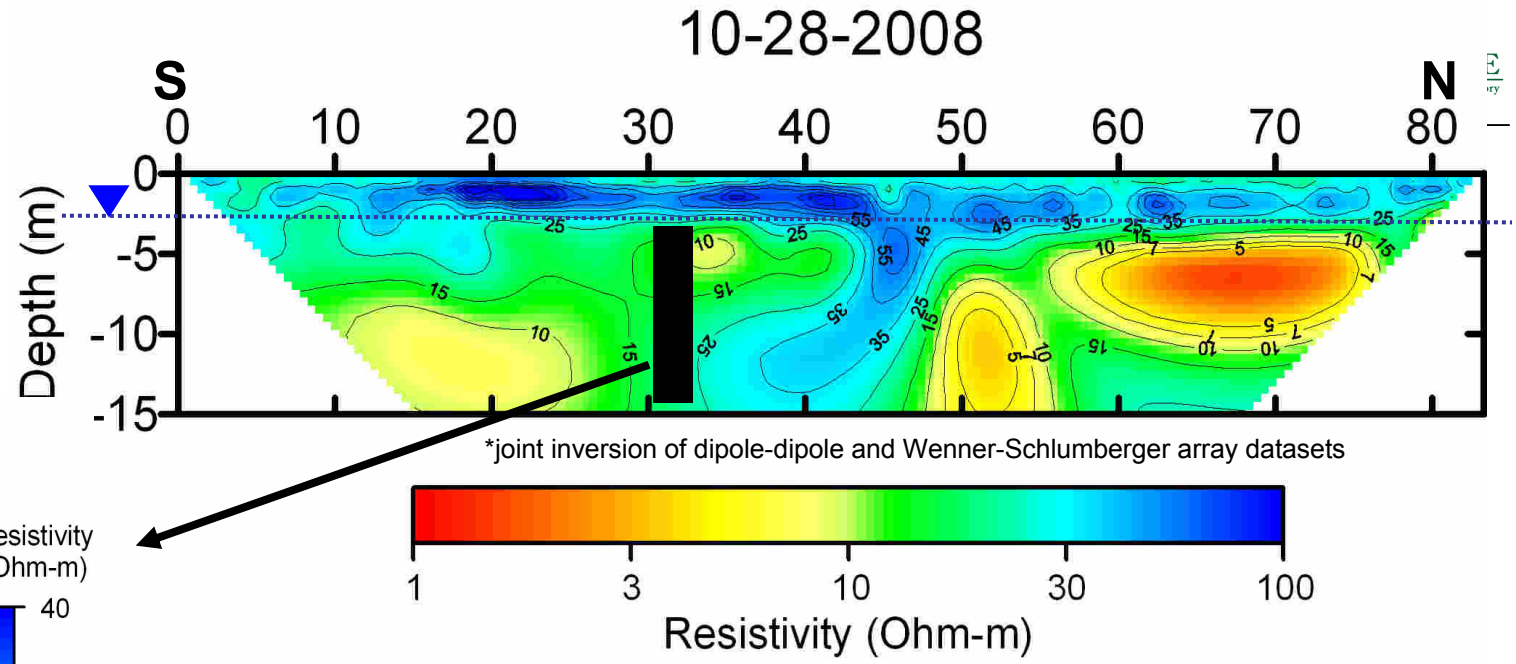


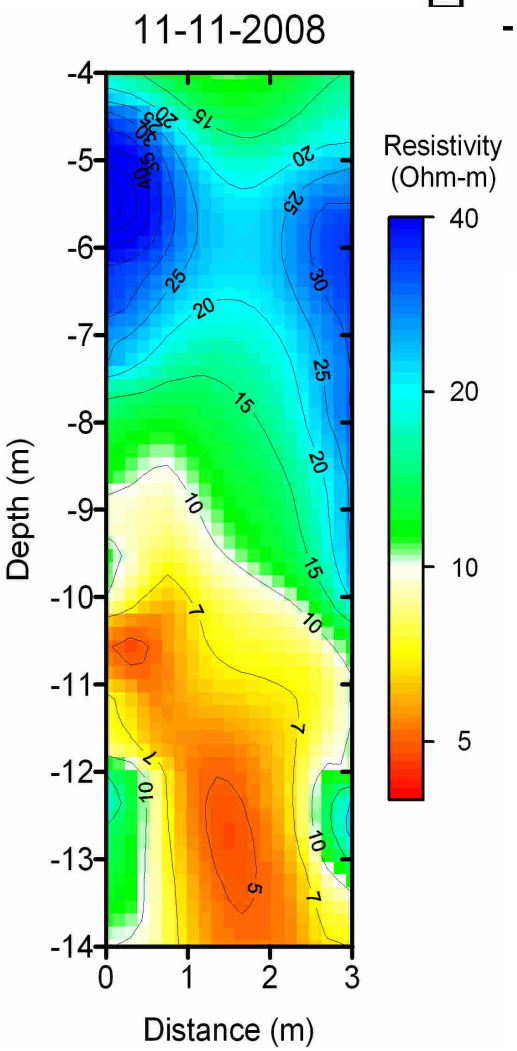
S-3 Ponds Recharge Hydrogeochemical-Geophysical Monitoring Study Area

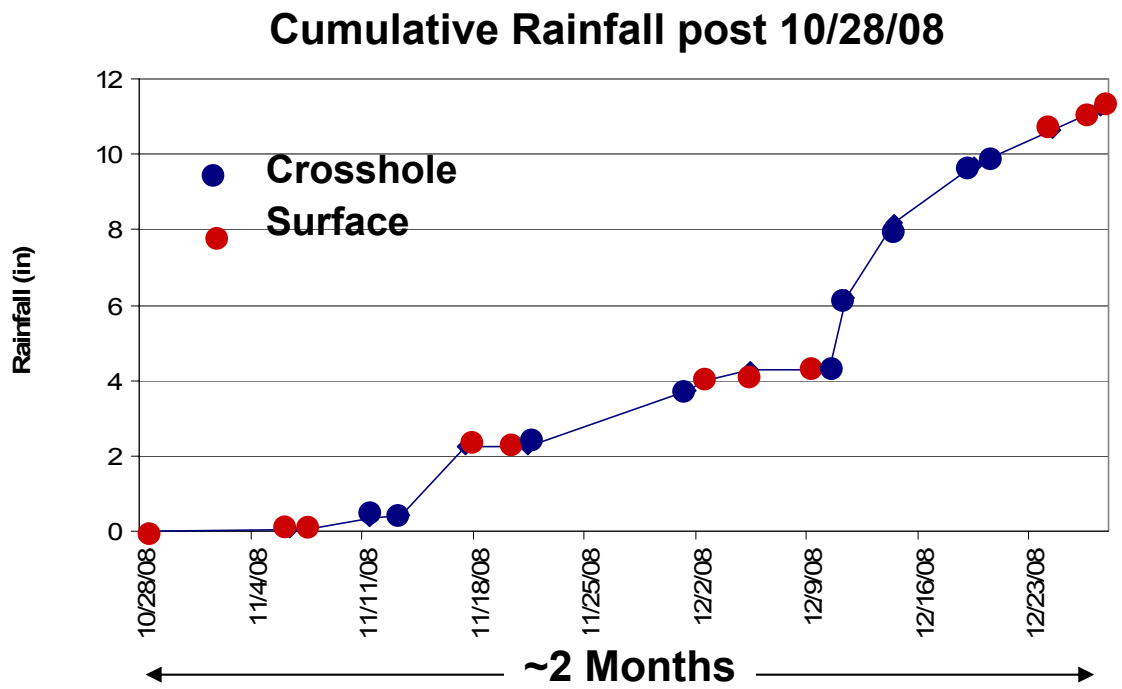


100m

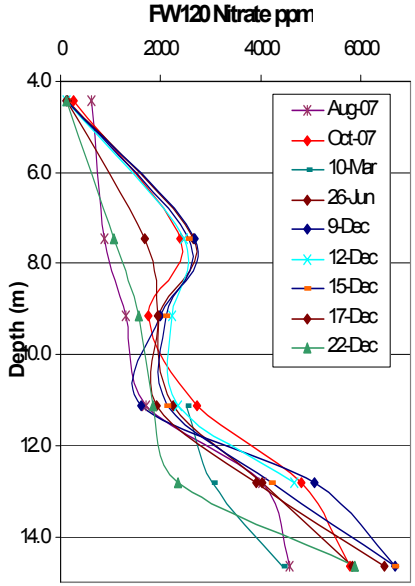
Electrical Imaging near S-3 During Dec. Storms: MOVIES

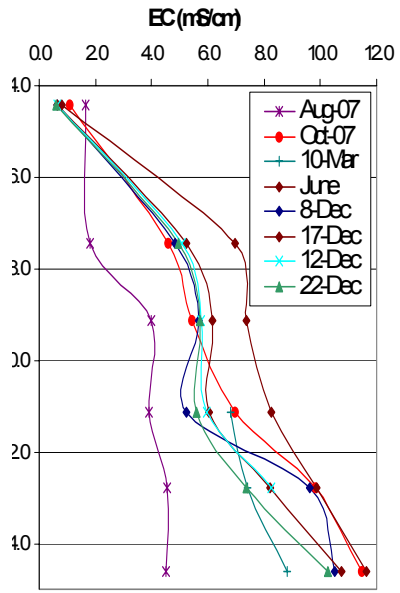


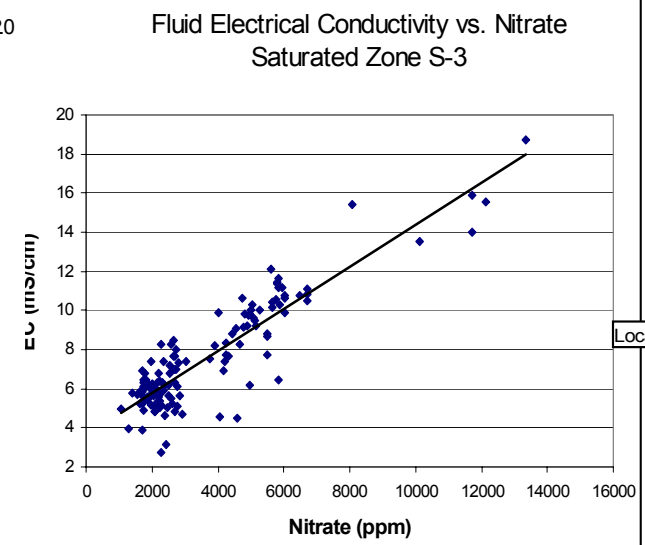


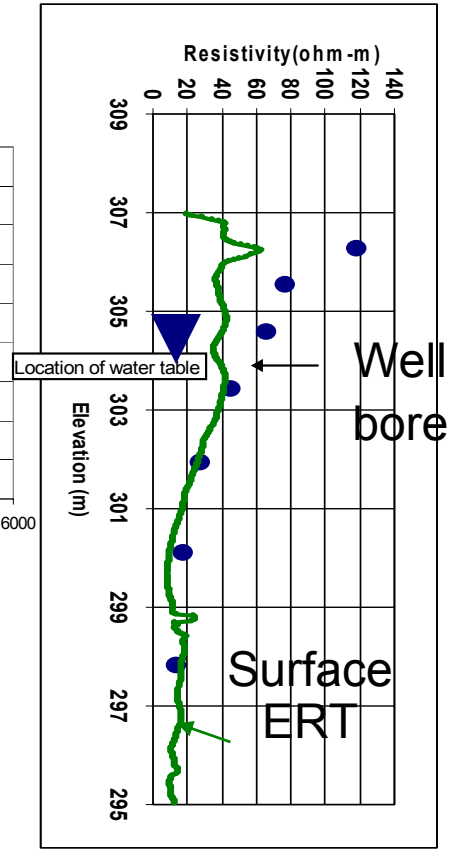


Electrical Observations and Approach for Quantitative Watershed Monitoring









'Scaling' comparison between resistivity estimation from surface profiling and wellbore measurements.

- **Scale:** Electrical measurements collected using wellbore and crosshole show consistent changes over scales and time. Scale matching between crosshole and surface is confounded by anisotropy and is under investigation.

- **Petrophysics**: Good relationship between saturated zone EC, Nitrate Concentration, and other geochemical parameters.

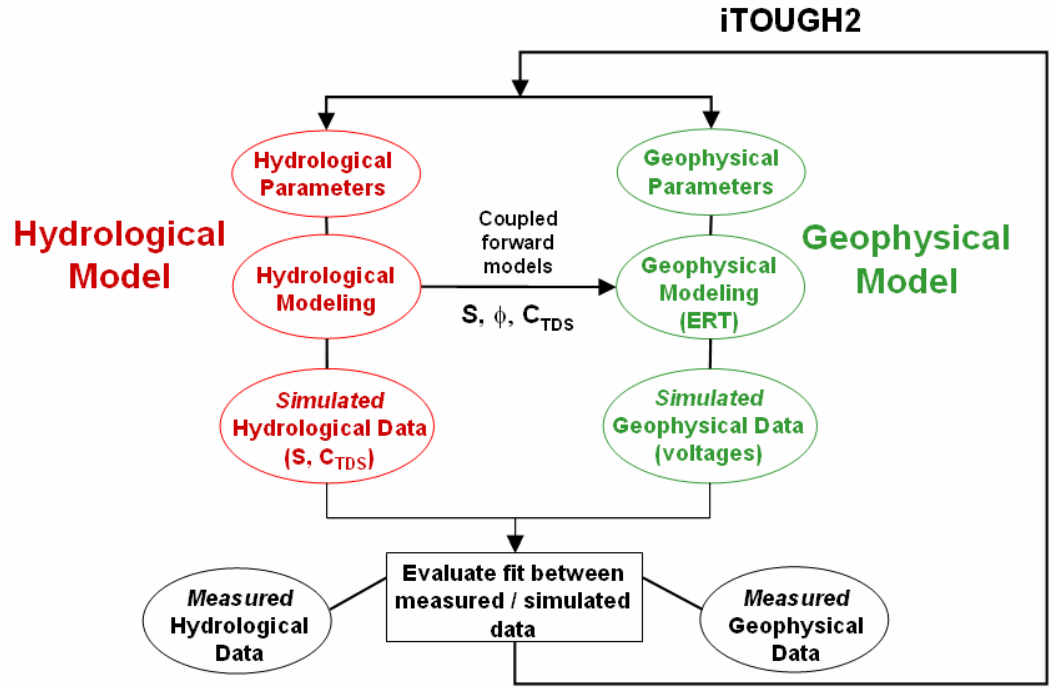
- Use **Coupled Modeling** to explore relative sensitivity of electrical methods to different recharge-related processes as a function of heterogeneity, distance from source, and scale……

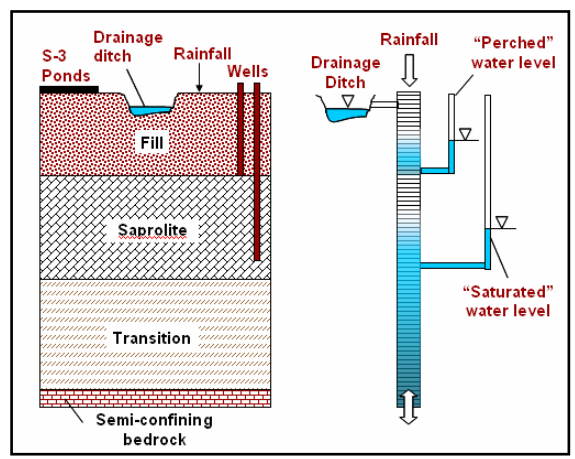
OAK RIDGE IFRC

Development and testing of Coupled Hydrogeophysical Flow Model

for quantitatively interpreting the geophysical data in terms of hydrogeochemical properties and dynamics

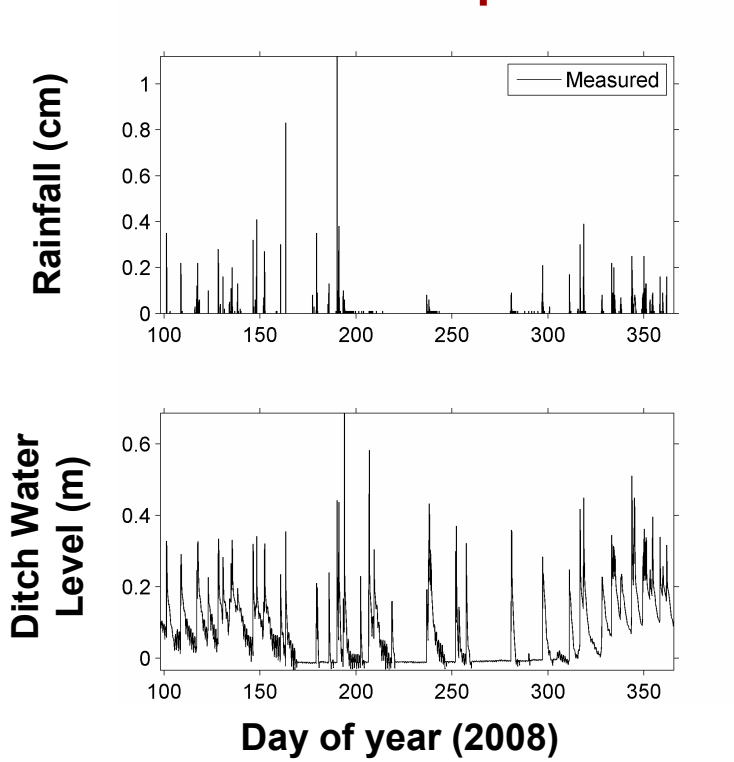
- Calibration of 1-D and 2-D models using 2008 data sets
  - Rainfall rates and ditch water levels
  - Water levels in perched/saturated zone
  - Dec. Nitrate Concentrations
- Coupled hydrogeochemical-ERT model allows
  - Joint interpretation of time-lapse ERT and hydrochemical datasets
  - *Understanding ERT sensitivity to time-varying hydrogeochemical parameters (e.g., saturation, and nitrate profiles)*
  - Development of petrophysical relationships and uncertainties.
  - Examination of scaling from local to regional



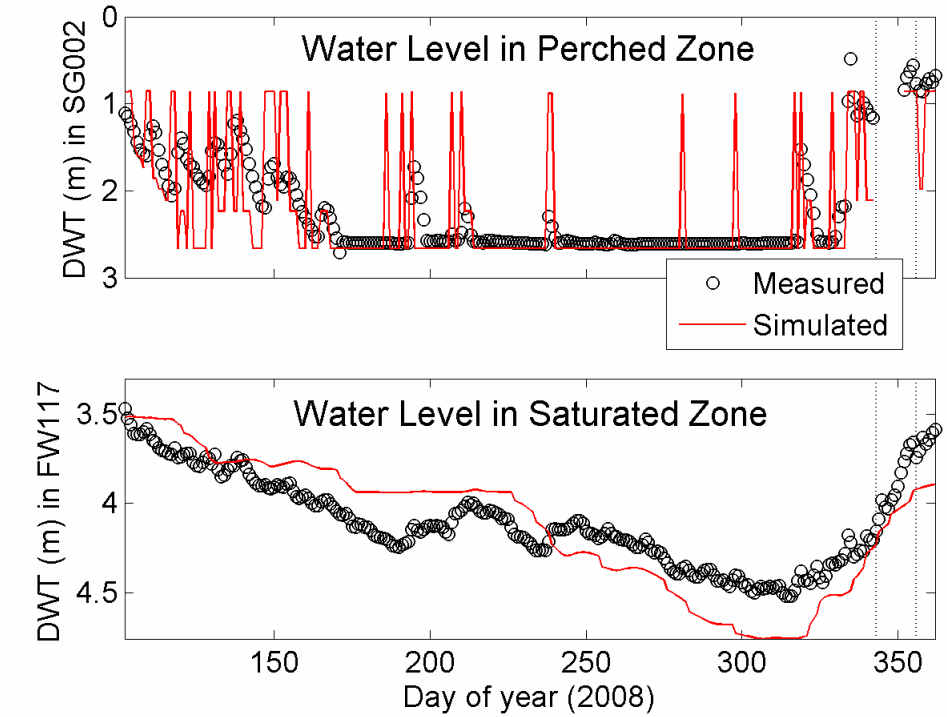


Hydrogeochemical Model Calibration

Model Input

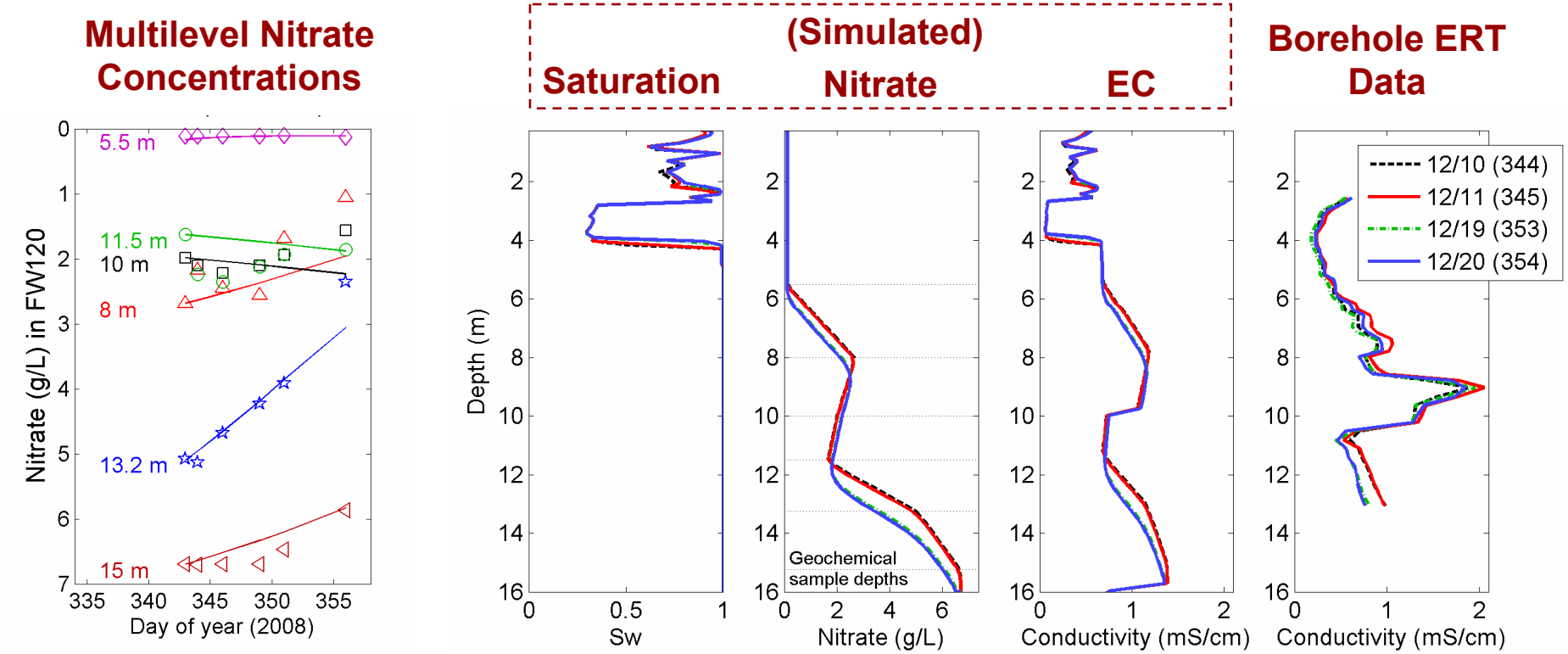


Model Output



- Water levels in perched and saturated zones and fluxes to deeper depths reproduced well in model calibration
- Incorporation of increasingly complex processes (2-D, fracture-matrix interactions, etc.) in progress.

Predicting Nitrate Transport and Electrical Conductivity (EC)



- Predicted Nitrate concentrations reproduced reasonably well; complex phenomena near transition zone not yet captured.
- Resistivity calculated from simulated properties with petrophysical function compares well with borehole ERT data; peak near 9 m not yet reproduced.
- *Currently calibrating coupled hydrogeophysical model to directly simulate the ERT data together with the hydrogeochemical data; will improve understanding of ERT response to hydrogeochemical processes*

Summary

1. **Extensive Data Collection across Plume**
   - Geochemical
   - Hydrological
   - Geophysical
2. **Development of new monitoring methods**
   - TLSRT
   - Pelcap
3. **Developed new approaches for integrating disparate, multi-scale datasets**
   - Joint inversion for watershed architecture delineation
   - Coupled modeling for recharge process investigation
4. **Developing insights about properties and processes important for ORNL IFRC plume stewardship**
   - Laterally extensive low velocity zone
   - Various recharge-related geochemical processes linked to heterogeneity
   - Sensitivity of electrical data for quantifying recharge-related processes.

Understanding the impact of natural recharge on contaminant concentrations over time and watershed scales is expected to be important for guiding decisions associated with long term plume stewardship

Computational Requirements Joint Inversion

- NT-2: 55 CPUs, each CPU @ 3.6GHz. Ran for three days (12000 iterations) on the LBNL LRC cluster.
  - Data: topography, water table.
  - 55 sources, 2 meter source spacing, 0.5m receiver spacing 0.5m.
- S-3: 112 CPUs @3.6 GHz Ran one day only (5000) iterations.