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
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)

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.

Multi-Scale
- Comparison of wellbore, crosshole, and surface geophysical datasets suggest that multi-scale datasets provide information about heterogeneity.

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

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)

\[
f(A,B,V,\delta,\tau \mid T,W) \propto f(T \mid A,B,V,\delta,\tau)f(W \mid A,B)f(A,B)f(V)f(\delta)f(\tau)
\]
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

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

Differential weathering of competent dipping bedrock beneath saprolite?
Laterally Continuous?
Major flow pathway?

Drilling campaign planned for 2009.
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:

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

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

Eventual nitrate dilution in shallow groundwater due to rainfall?
Solid phase buffering decreases pH upon rainfall?

U desorbs with decreasing pH

Different Recharge-related Processes!
Permeable Environmental Leaching Capsules (PELCAPs)

Quantifying *in situ* Reactive Contaminant Behavior Across the Watershed

**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

Brian Spalding
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)
- 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
S-3 Ponds Recharge Hydrogeochemical-Geophysical Monitoring Study Area
Electrical Imaging near S-3 During Dec. Storms: MOVIES

Cumulative Rainfall post 10/28/08

- Crosshole
- Surface

~2 Months

*joint inversion of dipole-dipole and Wenner-Schlumberger array datasets
**Electrical Observations and Approach for Quantitative Watershed Monitoring**

- **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..............................
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
• 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.
• 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

7. **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.