Re-Discovering Remediation Hydrogeology

EKOS, Sao Paulo Brazil, 6 November 2007

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An Evolving Culture

• How ARCADIS Looks at Sites and Why
Project Performance
Project Performance

Number of Projects

Failure  Success  Exceeds Expectations

Lucky
Why the Range in Performance?

Critical Importance of Hydrogeology

Success with in-situ technologies begins and ends with hydrogeology:

Majority of groundwater remediation failures due miss interpretation of the hydrogeology
We Needed a New Approach

We decided we need to open the “Black Box”

- Correct Tools
- Mis-Interpretation
Aquifers are Heterogeneous and Anisotropic as a Rule
Groundwater Always Takes The Path of Least Cumulative Resistance
Average Groundwater Velocities Significantly Understate Actual Transport Velocities

Borden Tracer Simulation
Dispersion Does not Factor into Remedial Design

- We live in an Advective World
  - Transverse Dispersion is very small
  - Lateral Dispersion is *Diffusion Controlled*
Significant Implications for Groundwater Restoration

Small volume, large spread – the “lampshade” – Never Happen

Un-realistic Expectations

Rationalized volume-radius – near-zero transverse dispersivity

Observed Behavior
Classic Fate and Transport

- Persistent source: 10 ft x 10 ft, 20 mg/L
- Source plane
- Bounding envelope

- $\alpha_x = 3$ ft
- $\alpha_y = 0.3$ ft
- $\alpha_z = 0.03$ ft
We Have Complex Systems of Inter-bedded Soils
A more realistic concept of fate and transport
Extending the new fate and transport concept

Early plume development

Maturing plume

After source removal
Remedial Cost / Remedial Time

Mature Plume

Early plume development
Groundwater Gradients are not a Reliable Indicator of Groundwater Flow

Hydraulic Gradient

5000 meters
Every Monitoring Well Sampling Method Yields Strongly Biased Results

Tracer Studies Reveal Dramatic Variability In the Delivery of Groundwater, Reagents & Contaminants to Wells
Fluid Accommodation

“Everybody knows that you can only inject water at about 1/3 the rate you can extract it” (David Miller, 1970’s)

To inject an incompressible fluid into an aquifer something must give – either water must be displaced or the aquifer expands
Injection is not the same as Pumping

\[ K_s = 9.5 \text{ ft/day} \]
Pumping Test Mask Variability

- Results are biased low
- We can not identify higher permeability zones
- We Can quantify the bulk movement of water
- We need to do Tracer Tests to determine

363 ft/day
We must have a good CSM to assess sites and develop effective Remedial Strategies.

Data driven from Conceptual to Quantitative

Evolving – Inclusive of all data, NEVER used to censor or filter outliers

Conceptual Site Models

Remedy completion

Remedy operation and monitoring

Adaptive Design

Design basis

Remedy pilot testing

Injection tracer testing

Remedy selection

Exposure assessment

Regulatory framework

Contaminant mass transport analysis

Superficial flow characterization

Contaminant distribution mapping

Develop preliminary conceptual model

Define project objectives

Depositional environment

Regional hydrogeology

Facility operating history

Contaminant release data
Where is remediation hydraulics sending us?

- Improved understanding of rebound and ability to troubleshoot remediation systems

- Injection tracer testing will be required for reactive zone designs (there’s no truth like tracer truth)

- There will be limits on mass removal in some cases, due to storage of contaminant mass in immobile pore spaces (slow-kinetic processes have an advantage over fast-acting reagents)
We have to change the Way we Look as Sites

Superficiality

• The scale of our measurements are such that we are always sampling the effect not the process

• We were taught in school that this is the only way to characterize groundwater systems

• Recognition that we are only superficially characterizing our systems is of fundamental importance
The assumption of Superficiality underpins virtually all academic thinking for the last 150 years

“The specific discharge is a macroscopic concept and is easily measured. . . . The microscopic velocities associated with the actual groundwater paths are real, but they are probably impossible to measure. This work focuses almost exclusively with concepts of flow on a macroscopic scale . . . .”

“This last paragraph announces a decision of fundamental importance. When we decide to analyze groundwater flow with a Darcian approach, it means, that we are going to replace (actual behavior) with averaged descriptions of microscopic behavior . . . .”

Freeze & Cherry (1979) page 17
Shift in paradigm

“I consider it certain that we need a new conceptual model, containing the known heterogeneities of natural aquifers, to explain the phenomenon of transport in groundwater.”

Charles V. Theis, 1967

“Hydrogeology has been too much inclined toward hydraulics and solving of the flow equations, and not enough toward geology and understanding/describing the rock structure, facies and properties in a geologically realistic manner, thus proposing “exact” solutions, but to poorly posed problems”

Ghislain de Marsily, 2005
The Remediation Hydraulics domain

Observable aquifer characteristic (e.g., permeability, porosity, geochemistry)

representative elementary volume (REV)

avg k

classical Darcian hydrogeology

Remediation Hydraulics

Scale of observation
Responding to Heterogeneities

<table>
<thead>
<tr>
<th>Response</th>
<th>Outcome</th>
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<tbody>
<tr>
<td>Ignore Heterogeneities</td>
<td>Prepare to be humiliated</td>
</tr>
<tr>
<td>Overwhelm Heterogeneities</td>
<td>Required to achieve rapid cleanup</td>
</tr>
<tr>
<td>Use Existing Heterogeneities to Our Advantage</td>
<td>Treat mobile porosity</td>
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<tr>
<td></td>
<td>Extends cleanup interval</td>
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<tr>
<td></td>
<td>Lowers overall cost</td>
</tr>
<tr>
<td>Create Useful Heterogeneities</td>
<td>Hydrofracture low-K formation</td>
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<tr>
<td></td>
<td>Creates high-flow path</td>
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<td>Groundwater bypasses contamination</td>
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Aquifer heterogeneities and the challenges they entail provide an opportunity for practitioners to distinguish themselves.

Seize the opportunity.

It’s the legacy.
Sustainable Water Resource Management