DYNAMIC GROUNDWATER RECIRCULATION AND ADAPTIVE DESIGN CONCEPTS:

Don’t accept the status quo

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Learning Objectives

After attending this presentation, you should be able to:

- **Define** Dynamic Groundwater Recirculation (DGR)
- **Explain** why DGR works
- **Describe** how DGR different from pump and treat
- **Recognize** the dominant factor that limits the overall pace of restoration
- **Identify** enhanced remedial strategies that can overcome back-diffusion and accelerate large plume restoration
What is Dynamic Groundwater Recirculation

- Enhances advective flushing – by focusing flow through preferential and less-preferential flow paths
- Creates dynamic flow regime mimicking natural conditions
- **Strategy recognizing the complexity of site conditions – Soil, GW, & Plume**
The Resurgence of Pump & Treat

• For L.P. we need to do containment – DGR is a more efficient approach
• For reagent delivery – In situ treatment is a contact sport, DGR drives more efficient distribution
• Remedial Strategies – It can be an important element of combined Remedies
• To understand why DGR work – we need to develop the appropriate CSM
The development of DGR parallels the evolution of ideas regarding contaminant transport through soils.

- Equivalent Porous media (REV)
- Dual-Domain
- Heterogeneous Stratigraphy
- Pump & Treat
- Directed Groundwater Recirculation
- Dynamic Groundwater Recirculation
Hydraulic conductivity in a 3-D aquifer

Summary

- Distribution should resemble the surface water patterns during deposition
- Each facies or layer should have the similar characteristics and be unique
- Hydraulic conductivity varies lognormally representing pathways of gravel grading to silts and clays
Aquifer division

(A) Sands and Gravels

Advective Zones – Pure Advection *(Mobile Fraction)*

(B) Silty/clayey sands

Advective & Storage Zones – Slow Advection *(Immobile Fraction)*
## Aquifer division

(C) Sandy Silts through Clays

Storage Zones – Static Water *(Stationary Fraction)*

### Summary

<table>
<thead>
<tr>
<th></th>
<th>Aquifer Fraction</th>
<th>Hydraulic Conductivity (cm/s)</th>
<th>Aquifer fraction</th>
<th>Hydraulic Conductivity (ft/day)</th>
<th>Groundwater Flow (%)</th>
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<td>A</td>
<td>Advective Zones Figure 6a</td>
<td>0.35</td>
<td>55%</td>
<td>120.8</td>
<td>92.5%</td>
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<td>1x10⁻²</td>
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<td></td>
<td>28.3</td>
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<td>B</td>
<td>Advective / Storage Zones Figure 6b</td>
<td>1x10⁻²</td>
<td>39%</td>
<td>9.69</td>
<td>7.4%</td>
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<tr>
<td></td>
<td>1x10⁻⁴</td>
<td></td>
<td></td>
<td>0.28</td>
<td></td>
</tr>
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<td>C</td>
<td>Storage Zones Figure 6c</td>
<td>1x10⁻⁴</td>
<td>6%</td>
<td>0.15</td>
<td>0.1%</td>
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<tr>
<td></td>
<td>3.5x10⁻⁶</td>
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<td></td>
<td>0.01</td>
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</table>
Re-thinking our conceptual model

**Adective Zones – Pure Advection (Mobile Fraction)**
- Sand & Gravel
- \( \text{Hydraulic Conductivity} > 10^{-2} \text{ cm/sec} \)

**Adective & Storage Zones – Slow Advection (Immobile Fraction)**
- Silty and Clayey Sand
- \( 10^{-4} < \text{Hydraulic Conductivity} < 10^{-2} \text{ cm/sec} \)

**Storage Zones – Static Water (Storage Fraction)**
- Sandy Silt, Silt, and Clay
- \( \text{Hydraulic Conductivity} < 10^{-4} \text{ cm/sec} \)

**Assumptions**
1. Heterogeneous-Advection
2. Diffusion
3. Depositional Environments
4. Anisotropic Flow
5. Tracer Studies
6. Mobile/Immobile Fractions
7. Dissolved Phase Storage
8. Mass Transfer Coefficients
9. Sequence stratigraphy
10. Transient flow
11. Static Fraction
12. Contaminant Assimilation
Simple Site: Concepts, P&T, DGR and Methods
Wastewater contaminated with TCE leaked from a lagoon into a sand and gravel aquifer. The ongoing release was identified after the on-site water supply well was impacted. Investigations revealed that the plume is 1,000 ft. in length, peak concentrations are 6,800 µg/L, and remedial objectives are 5 µg/L.
Groundwater

Flow Balance through plume

The plume is migrating southward toward the small streams and the constant head bounds to the south

\[ Q = K i A \]

\[ Q = 100 \text{ ft/day} \times 0.001 \text{ ft/ft} \times 175 \text{ ft} \times 41 \text{ ft} \]

\[ Q = 717 \text{ ft}^3/\text{day} \]

\[ Q = 3.73 \text{ gpm} \]

MNA Assessment

Estimated time for the plume to attenuate by dilution and discharge to the streams **34.4 years**
Pump and Treat System

One extraction well at the toe of the plume at 10 gpm.

Percent of the plume captured 99.65%

Estimated time to remediate the plume 31.8 years
A bigger Pump and Treat System

One extraction well at the toe of the plume at 20 gpm.

Percent of the plume captured 100.00%

Estimated time to remediate the plume 30.0 years
Simple DGR System

One extraction well and one injection well – each at 10 gpm

A recirculation cell is established, with nearly 100% of injected groundwater, captured
Simple DGR System

One extraction well and one injection well – each at 10 gpm

Percent of the plume captured 98.93%

Estimated time to remediate the plume 29.0 years
Bigger DGR System

One extraction well and one injection well – each at 20 gpm

A recirculation cell is established, with nearly 100% of injected groundwater, captured.
Bigger DGR System

One extraction well and one injection well – each at 20 gpm

Percent of the plume captured 99.99%

Estimated time to remediate the plume 24.3 years
A better DGR System

2 extraction wells
3 injection wells –
20 gpm of recirculated GW

Again, nearly
100% of injected groundwater is captured, but the width of the capture zone is narrower.
A better DGR System

2 extraction wells
3 injection wells – 20 gpm of recirculated GW

Percent of the plume captured 99.95%

Estimated time to remediate the plume 15.1 years
A General Design Approach
Technical Approach

• A batch flushing model is a simple yet effective method to assess remedy performance. This model estimates the amount of water that needs to be pumped for concentrations in a plume to decline from measured concentrations to remedial objectives.

• This model is widely applied to estimate remedy performance as the necessary data for application is routinely collected, and it has been found to provide reasonable estimates.


• The basic equation for the batch flushing model is presented as Equation (1) on the following slide.
The “Batch Flush Model”

Equation (1) \[ N_{PV} = R_f \ln \left( \frac{C_o}{C_f} \right) \]

Equation (1) can be divided by the \( R_f \) and raised to the “e-power”

\[ e^{\left( \frac{N_{PV}}{R_f} \right)} = \frac{C_o}{C_f} \]

Equation (2)

\[ C_f = C_o e^{\left( -\frac{N_{PV}}{R_f} \right)} \]

Equation (2) can be written more generally as the concentration reduction as a function of the number of pore volume flushes

Equation (3) \[ C = C_o e^{\left( -\frac{PF}{R_f} \right)} \]


Variable Definitions

\( C_o = \) Observed concentrations [M/L^3]
\( C_f = \) Final concentrations [M/L^3]
\( R_f = \) Retardation factor [--]
\( N_{PV} = \) Number of pore flushes to reduce concentrations from \( C_o \) to \( C_f \) [--]
\( PF = \) Pore volume flush [--]
The “Batch Flush Model” (continued)

The number of pore volume flushes (PF) in Equation (3) is the ratio of the aquifer volume to the volume of water flushed through the aquifer.

Equation (4) \[ PF = \frac{\text{aquifer volume}}{\text{extracted water volume}} = \frac{V_t}{Qt} \]

Substituting Equation (4) into Equation (3) we can compute changes in concentration as a function of time, the initial concentration, the aquifer volume, and the groundwater extraction rate.

Equation (5) \[ C(t) = C_o e^{-\left(\frac{V_t}{Qt}\right)/R_f} \]

Variable Definitions

- \( V_t \) = Total Aquifer Volume [L^3]
- \( Q \) = Groundwater Pumping rate[L^3/T]
- \( t \) = Time [T]
Design Data

• Contaminant Data
  – Properties – \( K_{oc} \), Degradation

• Regulatory – Remedial objectives (concentration)

• Plume conditions
  – Plume footprint (aerially and vertical)
  – Concentration ranges – average & maximum

• Aquifer/hydrogeology
  – Fraction of organic carbon \( (f_{oc}) \), hydraulic conductivity \( (K_s) \), bulk density \( (\rho_b) \), total porosity \( (\theta_s) \), sustainable yield from an extraction well
A Sample Problem
Sample problem - TCE plume

• **Summary:** Shallow unconfined aquifer impacted with TCE from the water table to the bottom of the aquifer

• **Aquifer:** The saturated aquifer thickness is 20 feet, $K_s = 20$ ft/day, The average sustained pumping rate is 20 gpm, The maximum sustained injection rate is 10 gpm. Total porosity estimated at 35%, the bulk density estimated $1.72 \text{ gm/cm}^3 \left[(1.0-0.35) \times 2.65\right]$, $f_{oc} = 0.08\%$

• **Plume:** 25 acres, average concentration 100 ppb, maximum concentration 1,000 ppb, remedial goal 5 ppb

• **Objective:** Clean up the aquifer to 5 ppb or less in 5 years
# Retardation Factor

<table>
<thead>
<tr>
<th>COC</th>
<th>Clean-up Goal (µg/L)</th>
<th>$K_{oc} (L/kg)^1$</th>
<th>Assumed $f_{oc}^2$</th>
<th>$K_d (L/kg)$</th>
<th>Total Porosity ($\theta_t$)</th>
<th>Bulk Density ($\rho_b$)</th>
<th>Retardation Factor</th>
</tr>
</thead>
<tbody>
<tr>
<td>PCE</td>
<td>1</td>
<td>94.94</td>
<td>0.0008</td>
<td>0.07595</td>
<td>35%</td>
<td>1.7225</td>
<td>1.37</td>
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<tr>
<td>TCE</td>
<td>1</td>
<td>60.7</td>
<td>0.0008</td>
<td>0.04856</td>
<td>35%</td>
<td>1.7225</td>
<td>1.24</td>
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<tr>
<td>cis-DCE</td>
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<td>39.6</td>
<td>0.0008</td>
<td>0.03168</td>
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<td>1.7225</td>
<td>1.16</td>
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<tr>
<td>VC</td>
<td>1</td>
<td>21.73</td>
<td>0.0008</td>
<td>0.01738</td>
<td>35%</td>
<td>1.7225</td>
<td>1.09</td>
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</table>

Calculations are based on the assumption of a clean sand aquifer.

$$R_f = 1 + \frac{K_d \rho_b}{\theta_t}$$

$$K_d = K_{oc} \times f_{oc}$$

References:
1 USEPA Region 9 RSL
2 EPA On-line Tools for Site Assessment Calculation, [https://www3.epa.gov/ceampubl/learn2model/part-two/onsite/i1c_onsite.html](https://www3.epa.gov/ceampubl/learn2model/part-two/onsite/i1c_onsite.html)

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**Variable Definitions**

- $K_{oc}$ = organic carbon-water partitioning coefficient
- $f_{oc}$ = fraction of organic carbon
- $K_d$ = distribution coefficient normalized to fraction of organic carbon
- $R_f$ = retardation factor
- $\theta_t$ = total porosity
- $\rho_b$ = bulk density
Basic Assessment

The Volume of water in the plume equals one pore volume

\[ V = 25 \text{ acres} \times 43,560 \frac{ft^2}{ac} \times 20 \text{ ft} \times 7.48 \frac{gal}{ft^3} \times 0.35 = 57.0 \text{ MG} \]

Applying Equation 1 using the average and maximum concentration we can compute the range in the pore flushes necessary to clean-up the aquifer

\[ N_{PV} = R_f \ln \left( \frac{C_o}{C_f} \right) \]

\[ N_{PV} = 1.24 \ln \left( \frac{100}{5} \right) = 3.71 \]

\[ N_{PV} = 6.57 \]
Basic Assessment

The Volume of water in the plume times the number of pore flushes equals the amount of groundwater that needs to be extracted from the plume.

\[ 57.0 \text{ MG} \times 3.71 = 211.8 \text{ MG} \]

to

\[ 57.0 \text{ MG} \times 6.57 = 374.7 \text{ MG} \]

Over a 5 year period of treatment, the annual pumping would be

\[ 211.8 \text{ MG} = 81 \text{ gpm for 5 years} \]

which at 20 gpm per well is

approximately 4 extraction wells

to

\[ 374.7 \text{ MG} = 142 \text{ gpm for 5 years} \]

which at 20 gpm per well is

approximately 7 extraction wells
Basic Assessment

If the objective is to inject 100% of the extracted water, we will need twice as many injection wells as extraction wells.

*The basic design for a 5-year period of performance will require 4 to 7 extraction wells and 8 to 14 injection wells. The treatment system capacity would be between 80 and 140 gpm.*
Full Scale Application
Background - former Rail Operating Facility

- Property transaction to private owner; terms include site remediation and schedule milestones
- Site Area – 12 Acres
- Primary Contaminants of Concern
  - Chlorinated Organics (VOCs)
  - PCBs
  - Metals
  - Petroleum

Challenge: How Quick Can Remediation Be Completed
Cross-section

• Soils
• Residual Sources
• Diffuse Plume
Combined Remedy

Installation/Completion of Three Separate Remedial Technologies

- Directed Groundwater Recirculation (DGR)
- Excavation
- Electric Resistivity Heating (ERH)

Designs were based upon maximum concentrations
### Basis for Design

<table>
<thead>
<tr>
<th>CVO</th>
<th>Clean-up Goal (ug/L)</th>
<th>$K_{oc}$ (L/kg)$^1$</th>
<th>Site foc</th>
<th>$K_d$ (L/kg)</th>
<th>Total Porosity</th>
<th>Bulk Density</th>
<th>Retardation Factor</th>
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</thead>
<tbody>
<tr>
<td>TCE</td>
<td>5</td>
<td>60.7</td>
<td>0.08%</td>
<td>0.04856</td>
<td>30%</td>
<td>1.855</td>
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<td>cis DCE</td>
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<td>39.6</td>
<td>0.08%</td>
<td>0.03168</td>
<td>30%</td>
<td>1.855</td>
<td>1.20</td>
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<tr>
<td>VC</td>
<td>2</td>
<td>21.73</td>
<td>0.08%</td>
<td>0.017384</td>
<td>30%</td>
<td>1.855</td>
<td>1.11</td>
</tr>
</tbody>
</table>

$^1$ USEPA Region 9 RSL

### Zone Details

<table>
<thead>
<tr>
<th>Zone</th>
<th>Area (ft²)</th>
<th>Volume of Groundwater (ft³)</th>
<th>Maximum Observed Concentration in Zone (ug/L)</th>
<th>Maximum Number of Pore Flushes per Zone</th>
<th>Rate Required for 15 month Closure (gpm)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>TCE</td>
<td>cis DCE</td>
<td>VC</td>
<td>TCE</td>
</tr>
<tr>
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<td>105,480</td>
<td>46</td>
<td>140</td>
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<td>3</td>
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<td>220,320</td>
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<td>8</td>
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<td>211,320</td>
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<td>3100</td>
<td>8000</td>
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Design
First Quarter Performance

5.8 MG Recirculated / Target – 5.6 MG
Second Quarter Performance

Thermal Began
Week 12

3.8 MG Recirculated / Target 8.3 MG
Third Quarter Performance

2.7 MG Recirculated / Target 11.1 MG
Fourth Quarter Performance

3.0 MG Recirculated / Target 13.9 MG
Performance – One Year

1.6 MG Recirculated / Target 6.9 MG
Summary

Groundwater Treatment

Targets: Extraction 41.7 MG / Injection 41.7 MG
Actuals: Extraction 19.9 MG / Injection 11.9 MG

Implications

• Measured groundwater concentrations tend to over estimate the total mass
  − Mass distribution is always heterogeneous from all perspectives
• Changing injection and extraction rates create dynamic horizontal and vertical gradients
• Dynamic gradients will tend to drive contaminants toward more permeable pathways
• Large diffuse plume can be remediated to less than remedial objectives
• Slow advective zone can be remediated / Low K storage zones need to be assessed
Dynamic Operation
Plume Development

Implications

- Plume Spread
- Variability in Concentrations
- Flow Divergence
- Changes in flow directions cause the flow pathways to change

The optimal remedy needs to unravel the natural transport process

If groundwater gradients can be managed – we can achieve superior performance.
What is Dynamic Groundwater Recirculation

- Enhances advective flushing – by focusing flow through preferential and less-preferential flow paths
- Creates dynamic flow regime mimicking natural conditions
- Strategy recognizing the complexity of site conditions – Soil, GW, & Plume
Chaotic Advection

Advective Mixing

Interdisciplinary Science
• food science, biology, precision manufacturing, geology, astrophysics

Bending and Folding
• Ottino (1990), Bagtzoglou et al. (2007), Mayers et al. (2012), Piscopo et al. (2013)

Our plumes developed through Change
Corollary

The optimal remedy needs to unravel the natural transport process

If groundwater gradients can be managed – we can achieve superior performance.

Controlled – pathways stop changing
3 Layer System
Five years

5-year plume development
Ten years
10-year plume development
20 years

5-years after the onset of remediation
25 years

10-years after the onset of remediation
35 years

20-years after the onset of remediation
45 years

30-years after the onset of remediation
15 years
16 years
19 years
22 years
24 years
24 years
Relative Travel Times
TCE Plume - 2004

- Primary Sources
- Landfill

Main Plume

~ 5 km

CSM
- Heterogeneous & Anisotropic Strategy
- Target the Mass Flux
Remedial Plan / Combined Remedy
- in situ bio & DGR
Extraction Wells & Rates - 2004

Total - 900 gpm
Site Wide

Step 1 – Hydraulic Containment
Improved Operation—350 gpm
Extraction Wells & Rates - 2009

Total - 300 gpm
How is DGR different from other reinjection approaches?

• Most pump and treat systems that include reinjection, focus on injecting the water as efficiently as possible with the fewest number of wells. This approach provides little benefit as most and sometimes all of the injected water does not flow towards the extraction wells.

• The proposed approach distributes injection wells along the periphery of the plume. This promotes restoration in low concentration areas away from extraction wells, focusing groundwater flow toward the extraction wells.
Reagent Delivery System
Large plumes can be cleaned up

Former Reese Air Force Base

~3 miles

2004

2012
Today’s Presenter

SCOTT POTTER
Chief Hydrogeologist

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e Scott.Potter@arcadis.com
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