Two Emerging Concepts About Groundwater Plumes: Matrix Diffusion and Mass Discharge

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Groundwater Plume Contaminant Transport

Test Tank with Dye
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Test Tank with Dye
Threat to Human Health and the Environment:

Drinking water well “captures” part of the plume so contaminants are brought to the surface and ingested.
Groundwater Plume Contaminant Transport

Key Concepts:

1. Contaminants in groundwater flow through sand layers surrounded by impermeable clay and silt.

2. We need to regulate the concentrations in groundwater (in units of micrograms per liter / parts per billion).
Two Emerging Concepts

Matrix Diffusion

• Process where low permeability zones become sources
• Difficult to get to the contaminant mass in low perm zone
• Creates a long “concentration vs. time tail”

Mass Discharge/Mass Flux

• Based on “loading” to a groundwater aquifer
• Different way to think about sites
• Recent advances in techniques
Real World: Heterogeneity Rules, Even in “Sandy Aquifers”

Image from Fred Payne /ARCADIS
Matrix Diffusion Explained

Advancing solvent plume  Low permeability silts  Transmissive sand

Expanding diffusion halo in stagnant zone

Simultaneous inward and outward diffusion in stagnant zones

After NRC 2005
Matrix Diffusion Movie
Doner and Sale, Colorado State University

Loading Phase

Day 1  Day 3  Day 5

Day 10  Day 15  Day 22
Matrix Diffusion Movie
Doner and Sale, Colorado State University

Flushing Phase

Day 24(2*)
Day 27(5*)
Day 31(11*)

Day 42(20*)
Day 74(52*)
Day 118(96*)
Key Point – Matrix Diffusion is a Small Scale Phenomena

Contaminant storage and release processes in low permeability zone is important, but it is governed by concentrations gradients that occur at scales of centimeters to millimeters.

To Download Movie: www.gsi-net.com
Aquifer – Aquitard Contact

Stratigraphic Column

~3 m
9 m
30 m

Upper Sand Aquifer
Silty Aquitard

Aquifer
Aquitard

Image Courtesy of B. Parker
High-Resolution Data from Core

Distance (m from Interface) vs. TCE (mg/L)

Aquifer
Continuity at Interface
Aquitard

$\rho_w = 1.95 \text{ g/cm}^3$
$f = 0.43$
$R = 1.2$

Chapman and Parker 2005
Image Courtesy of B. Parker
Connecticut Site

Groundwater Flow

Transect 1

Source Zone

3000 kg TCE present in low-perm zone!

Groundwater Flow

500 ft
Two Emerging Concepts

Matrix Diffusion
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Key Reference: ITRC Mass Flux / Mass Discharge Guide
Google “ITRC Mass Flux”
Consider Two Sites With Same Maximum Concentration

**Site M:** Mega Site  
Big Source, Extreme Hi GW Velocity

**Site P:** Small Site  
Small Source, Almost Stagnant

“Well Snapper”  
“PASU”
Definitions

MASS DISCHARGE

- The total mass of any solute conveyed by a plume at a given location in units of mass per time.

Symbol: $M_d$

Units:
grams per day or kilograms per year
Definitions

Mass flux, $J$

Integrate

Mass discharge, $M_d$

"This plume has a mass discharge of 1.5 grams per day."

Sir Isaac Newton:

"Method of Fluxions"
Five Methods for Mass Discharge

- **Method 1**: Transect Method
- **Method 2**: Well Capture/Pumping Methods
- **Method 3**: Passive Flux Meters
- **Method 4**: Using Existing Data (Isocontours)
- **Method 5**: Solute Transport Models

All methods are “ready to go”
**Method 1: Transect Method**

1. Characterize plume and flow (q and C)
2. Select transect: with simple approach, build cross-sectional polygons ("window panes") for each well
3. Determine area (W • b = A)
4. Multiply terms and sum:

\[ M_d = \sum (C_n \cdot A_n \cdot q) \]

- \( M_d \) = Mass discharge
- \( C_n \) = Concentration in polygon n
- \( A_n \) = Area of segment n

Nichols and Roth, 2004
High Resolution Mass Flux Transect

(a)

New Hampshire PCE Site

Ground

Water Table

M_d: 56 grams per day (Mag 6 Plume)

Source: Guilbeault et al., 2005
Methods 3 – Passive Flux Meter

- **Permeable sorbent**
  - Accumulates contaminant based on flow and concentration

- **Soluble tracers**
  - Loses tracer based on groundwater velocity and flux convergence calculations

1. Contaminant adsorbed onto passive flux meter over time to get **Concentration**

2. Tracer desorbs from passive flux meter over time to get **Flow (Q)**

Source: Hatfield and Annable

Photo: Dye intercepted in a meter

Groundwater Flowlines
Passive Flux Meter

Installation

Sampling

Vendor: http://www.enviroflux.com/pfm.htm
Method 5: REMChlor Model of Source Remediation

Remove 90% of mass in 2010. REMChlor shows mass discharge vs. distance in future years

Distance from Source (meters)

2008

2014

2080

Mass Discharge (Kg per year)

Author: Ron Falta, Clemson Univ.
Google: “REMChlor EPA”
Use mass discharge of plume to predict constituent of concern concentration in downgradient water supply well

\[
C_{\text{well}} = \frac{M_d}{Q_{\text{Well}}}
\]

\(C_{\text{well}}\) = Concentration in extraction well
\(Q_{\text{well}}\) = Pumping rate for extraction well

\(M_d = 2\) grams/day

\(Q_w = 600\) gpm

\[
\frac{2 \text{ g/day} \times \frac{1}{600 \text{ gpm}} \div 1440 \text{ min} \times \frac{1 \text{ gal}}{3.79 \text{ L}} \times \frac{10^6 \text{ ug}}{\text{ g}}}{1 \text{ ug/L}} = < 1 \text{ ug/L}
\]

Einarson and Mackay, 2001
# Plume Magnitude Classification System

<table>
<thead>
<tr>
<th>Mass Discharge (grams/day)</th>
<th>Plume Category</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt; 0.001</td>
<td>“Mag 1 Plume”</td>
</tr>
<tr>
<td>0.001 to 0.01</td>
<td>“Mag 2 Plume”</td>
</tr>
<tr>
<td>0.01 to 0.1</td>
<td>“Mag 3 Plume”</td>
</tr>
<tr>
<td>0.1 to 1</td>
<td>“Mag 4 Plume”</td>
</tr>
<tr>
<td>1 to 10</td>
<td>“Mag 5 Plume”</td>
</tr>
<tr>
<td>10 to 100</td>
<td>“Mag 6 Plume”</td>
</tr>
<tr>
<td>100 to 1,000</td>
<td>“Mag 7 Plume”</td>
</tr>
<tr>
<td>1,000 to 10,000</td>
<td>“Mag 8 Plume”</td>
</tr>
<tr>
<td>10,000 to 100,000</td>
<td>“Mag 9 Plume”</td>
</tr>
<tr>
<td>&gt;100,000</td>
<td>“Mag 10 Plume”</td>
</tr>
</tbody>
</table>

Newell et al., accepted Journal of Ground Water
## What Mag Plume Does It Take for Impact?

**For complete capture and MCL = 5 ug/L:**

<table>
<thead>
<tr>
<th>Mass Discharge (grams/day)</th>
<th>Plume Classification</th>
<th>This Mag Plume Could Impact:</th>
</tr>
</thead>
<tbody>
<tr>
<td>0.001 to 0.01</td>
<td>Mag 2 Plume</td>
<td><strong>Domestic well</strong> pumping at 150 gallons/day</td>
</tr>
<tr>
<td>1 to 10</td>
<td>Mag 5 Plume</td>
<td><strong>Municipal well</strong> pumping at 100 gallons per minute</td>
</tr>
<tr>
<td>1,000 to 10,000</td>
<td>Mag 8 Plume</td>
<td><strong>Stream</strong> with a mixing zone and base flow of 100 cubic feet per second</td>
</tr>
</tbody>
</table>

Newell et al., accepted Journal of Ground Water
Summary

Two Emerging Concepts

- Matrix Diffusion
- Mass Discharge/Mass Flux

Why Now?

- Groundwater sites very difficult to remediate
- New thinking about processes and management strategies

Implications

- Matrix diffusion can result in persistent low level concentrations even after remediation
- Might consider tailoring site characterization/performance monitoring projects to include mass flux/mass discharge