Field Trials of Chaotic Advection to Enhance Reagent Delivery

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Challenges in Remediation: Mixing

- For desired *in situ* reactions to occur, the injected reagent and contaminant must first come into contact
- In porous media, effective mixing is challenging:
  - Laminar flow
  - Molecular diffusion very slow
  - Preferential flow paths

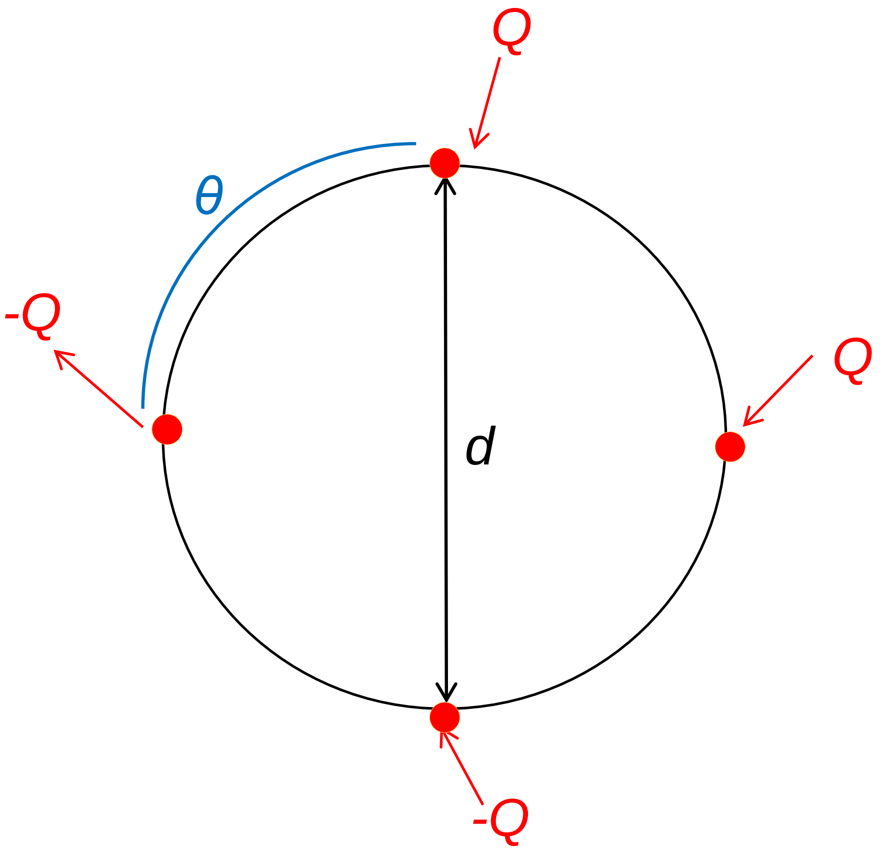
Chaotic Advection

- Class of flows in which fluid particles that are initially nearby may travel very different paths
- Repeated stretching and folding of fluid parcels
  - Creates fluid elements stretched out into thin filaments with length scale for diffusion to contribute to more efficient mixing

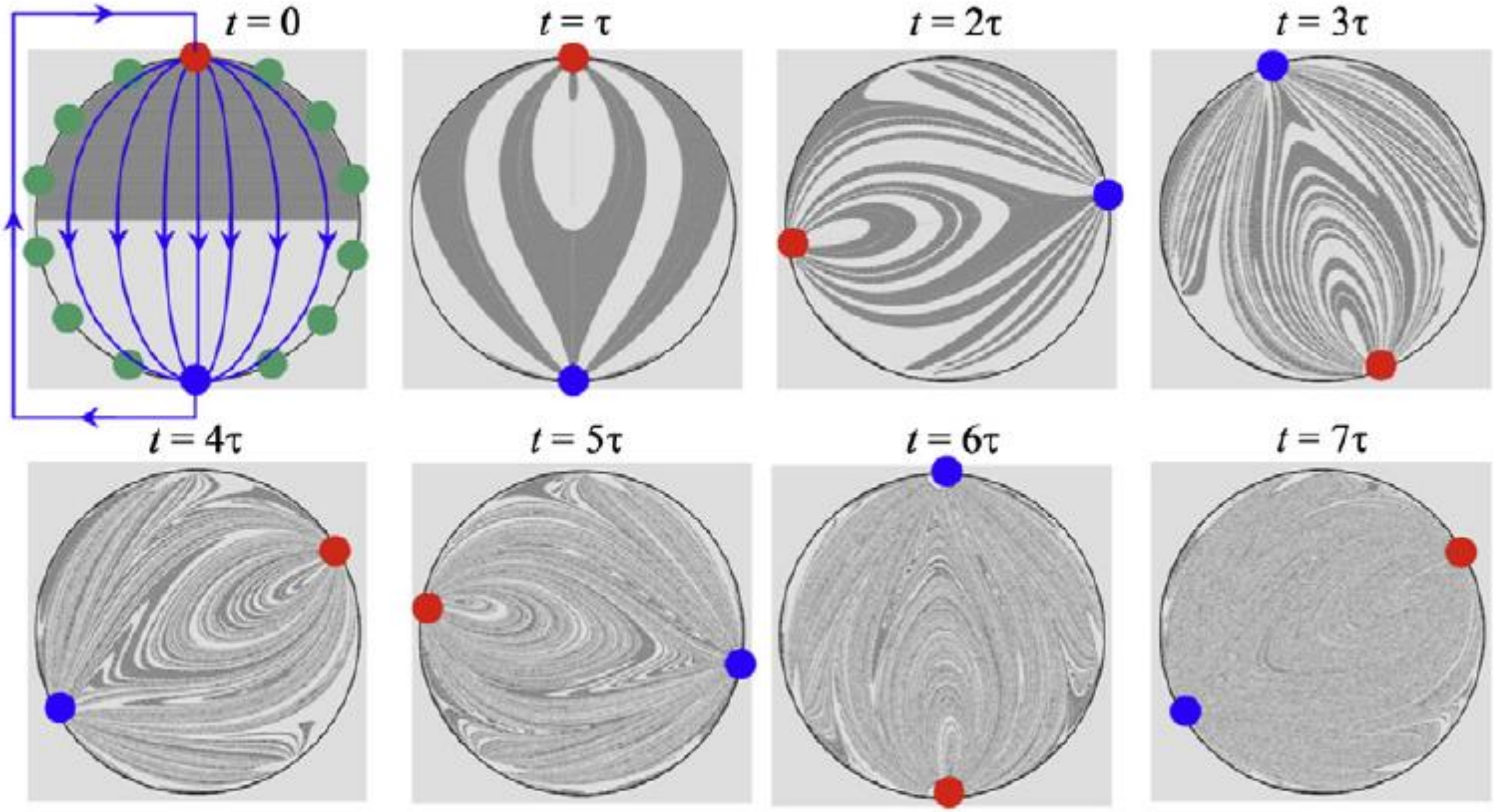
Metcalfe et. al / AlChe J. 52 (2006), 9-28

Chaotic Advection: RPM FLOW

- **Rotated Potential Mixing:**
  - Transient switching of flow at a series of radial wells
  - A dipole well pair operates at a flow rate (Q) for a specified duration of time before being re-oriented by angle, θ
  - This sequence is repeated around the well network



Chaotic Advection

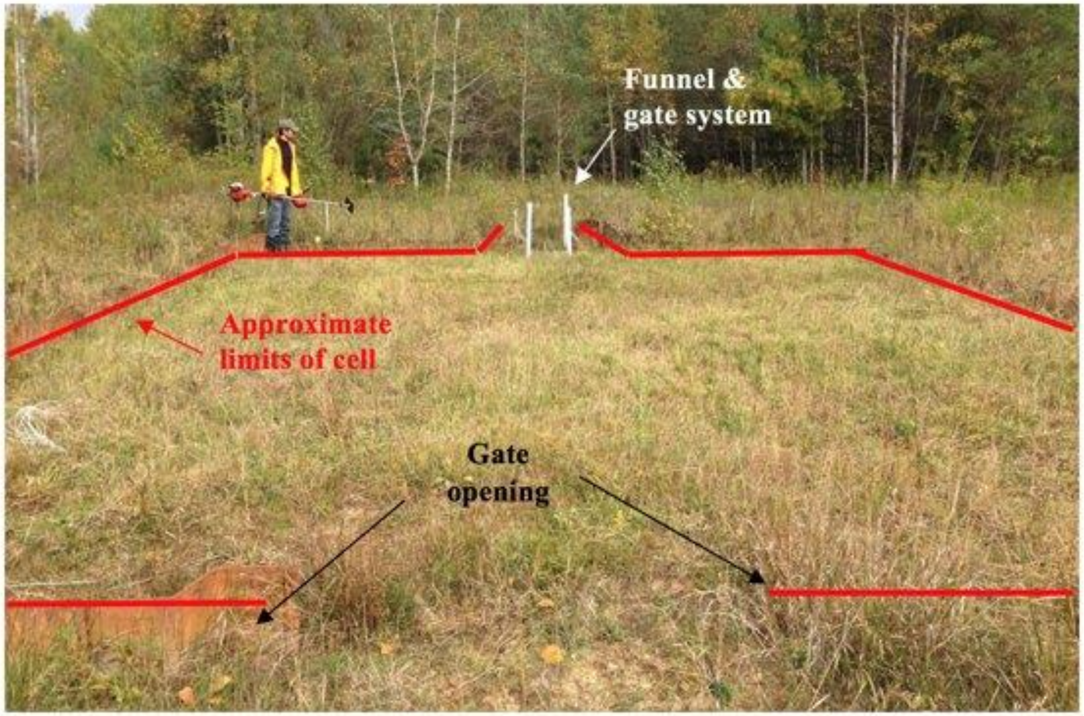


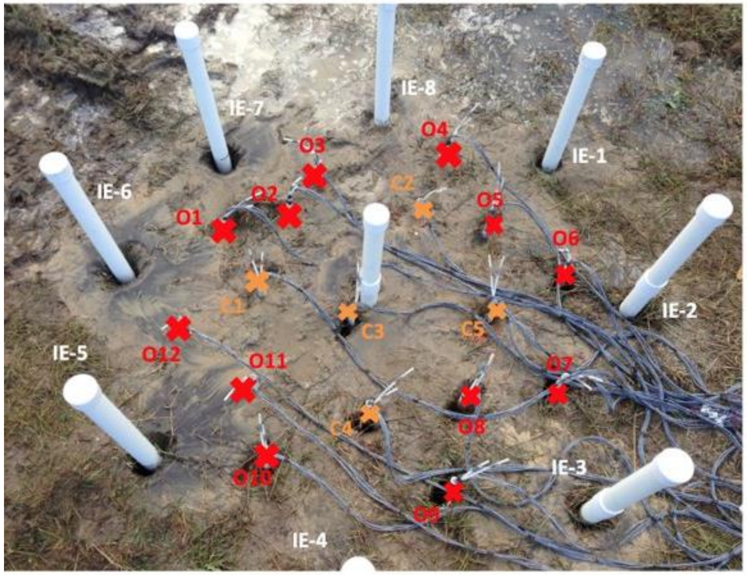
Trefry et al. / J. Contam. Hydrol. 127 (2012) 15-29

Objectives

- Investigate the feasibility of an RPM flow protocol to generate engineered chaotic advection in a natural aquifer system
- Develop quantitative methods to demonstrate the presence of chaotic advection and its impacts on mixing based on the spatial and temporal resolution of field data

Field Site: CFB Borden





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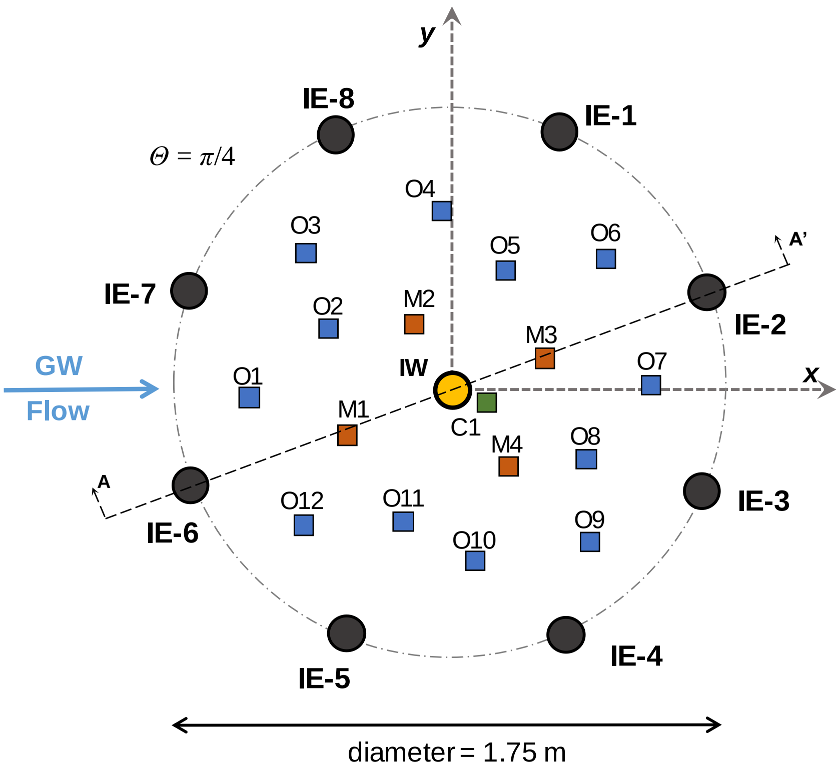
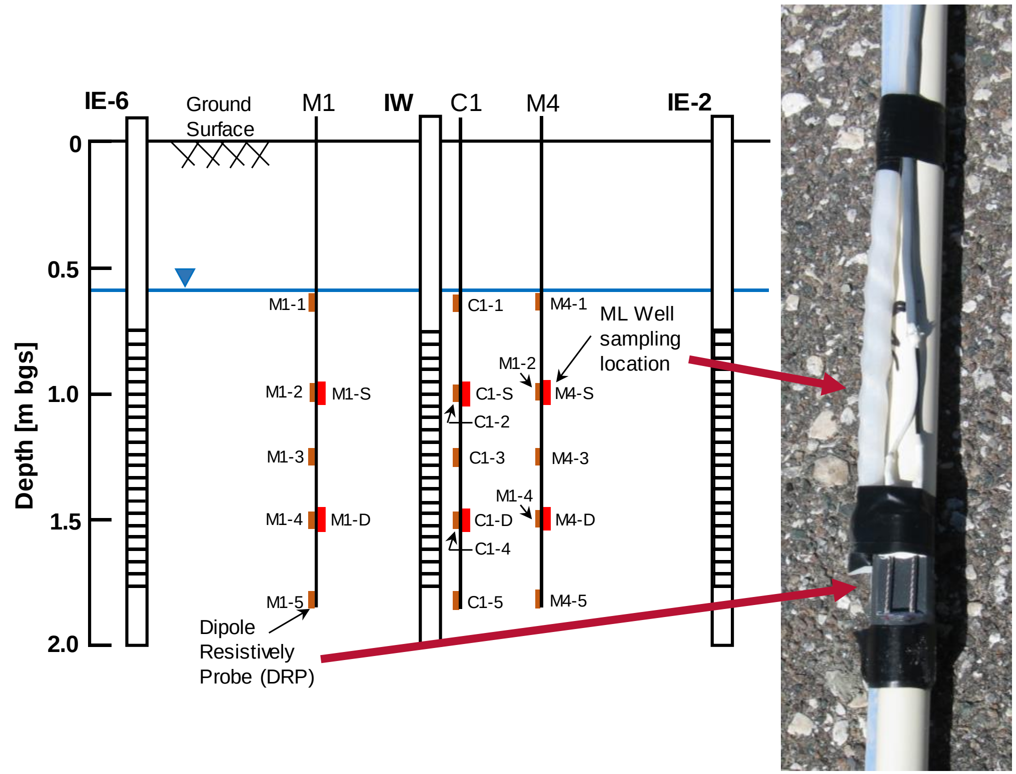
Methods





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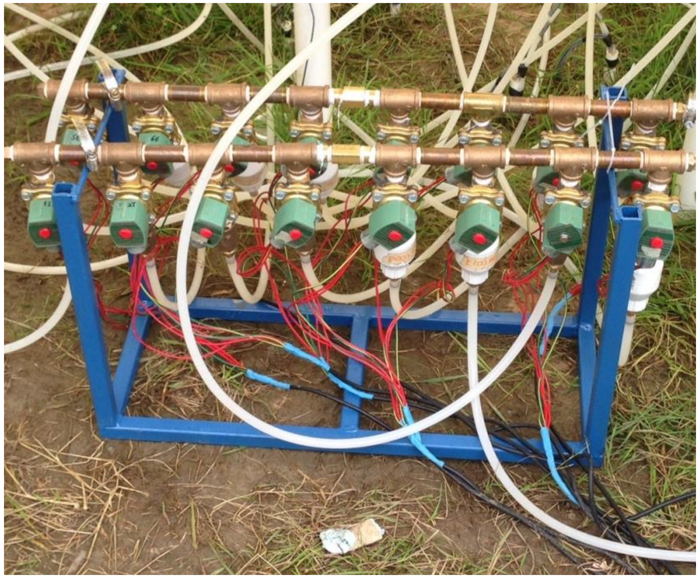
Methods

- Mixing Test, RPM45-A
  - Injection (10 g/L of NaCl, 0.5 hours)
  - Equilibrium (~24 hours)
  - Mixing (168 hours or 7 days)
  - Extraction (9 days)

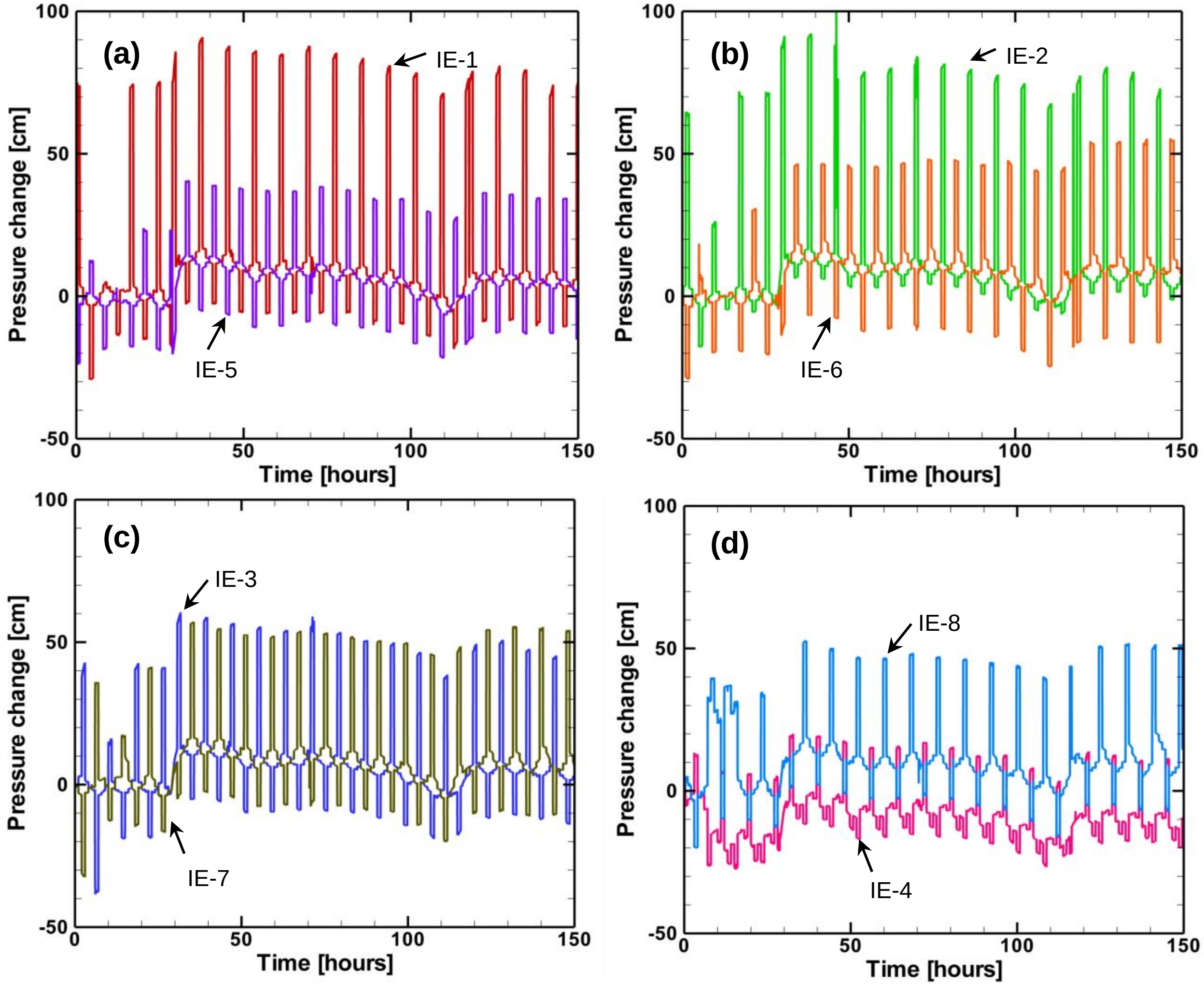
Parameter	Values
Flow rate, Q (LPM)	~2
Pumping duration, t (hrs)	1
Re-orientation angle, Θ	45^o
Diameter between wells, d (m)	1.75
Number of iterations, n	21



Methods

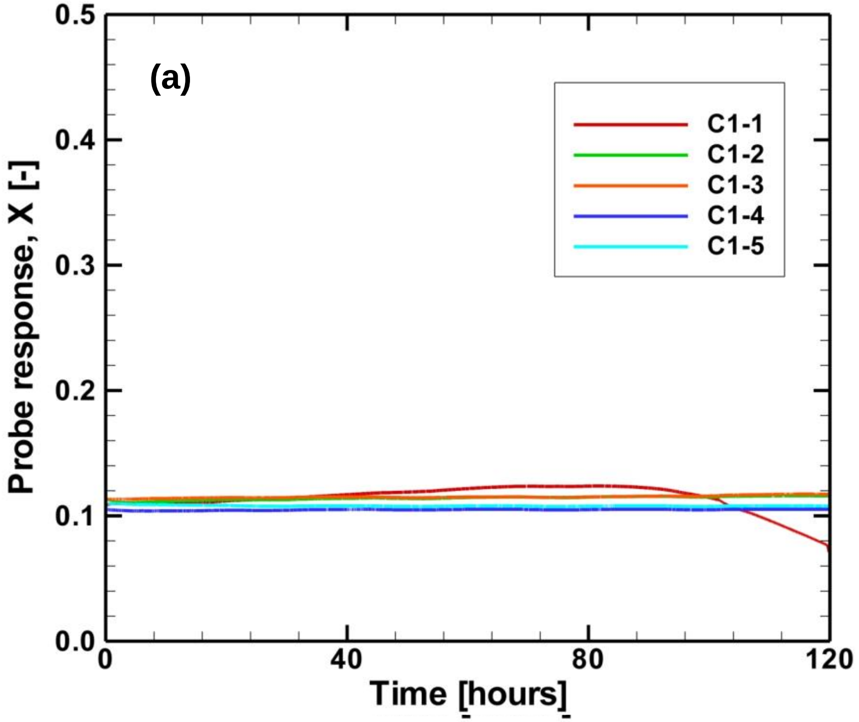
- Control test, CTR1-A
  - Injection (1 g/L of NaCl, 0.5 hours)
  - Natural mixing (5 days)
  - Extraction (8 days)

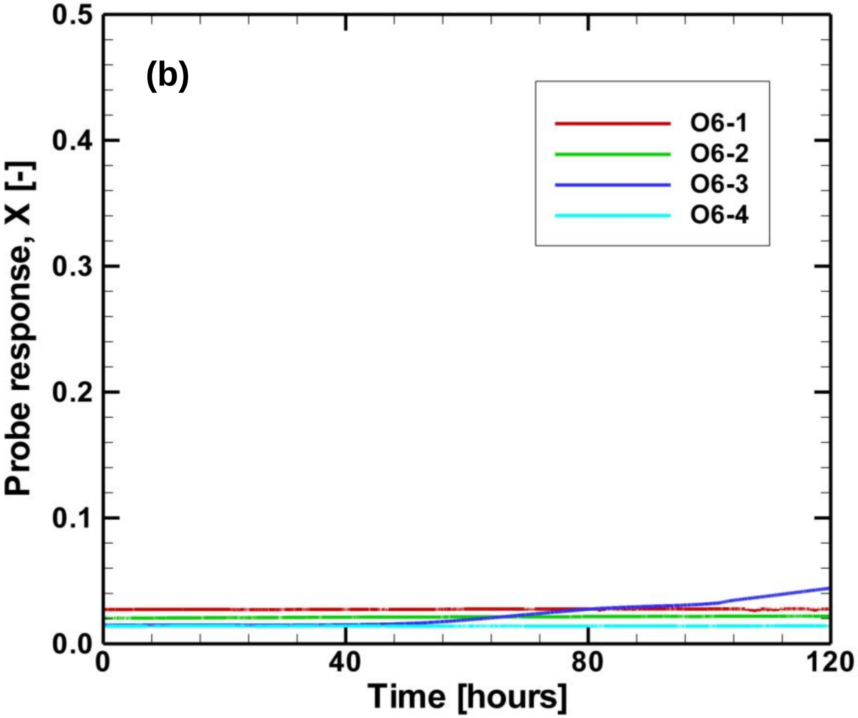
Key Results: Hydraulic Data



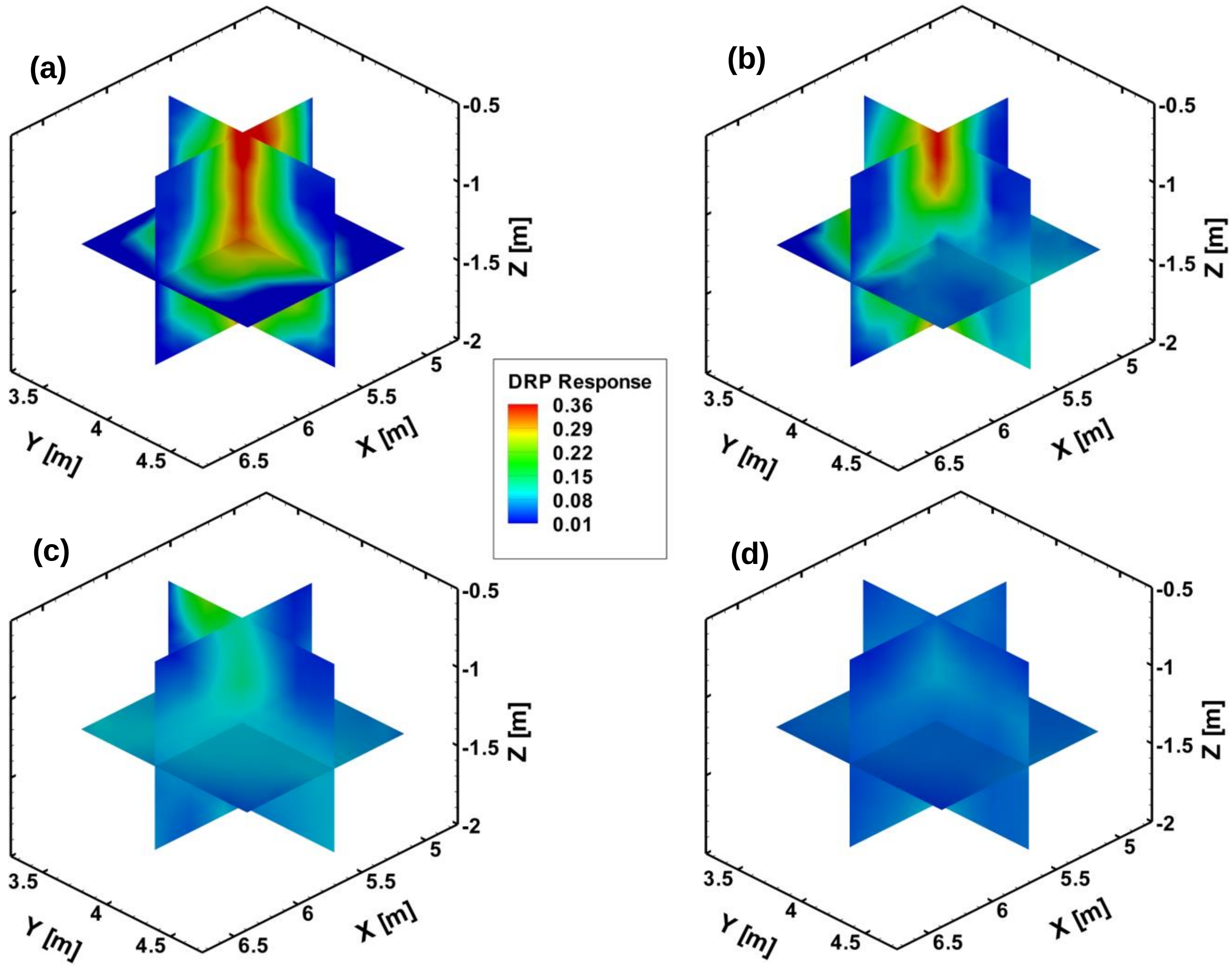
Key Results: Breakthrough Curves

CTR1-A

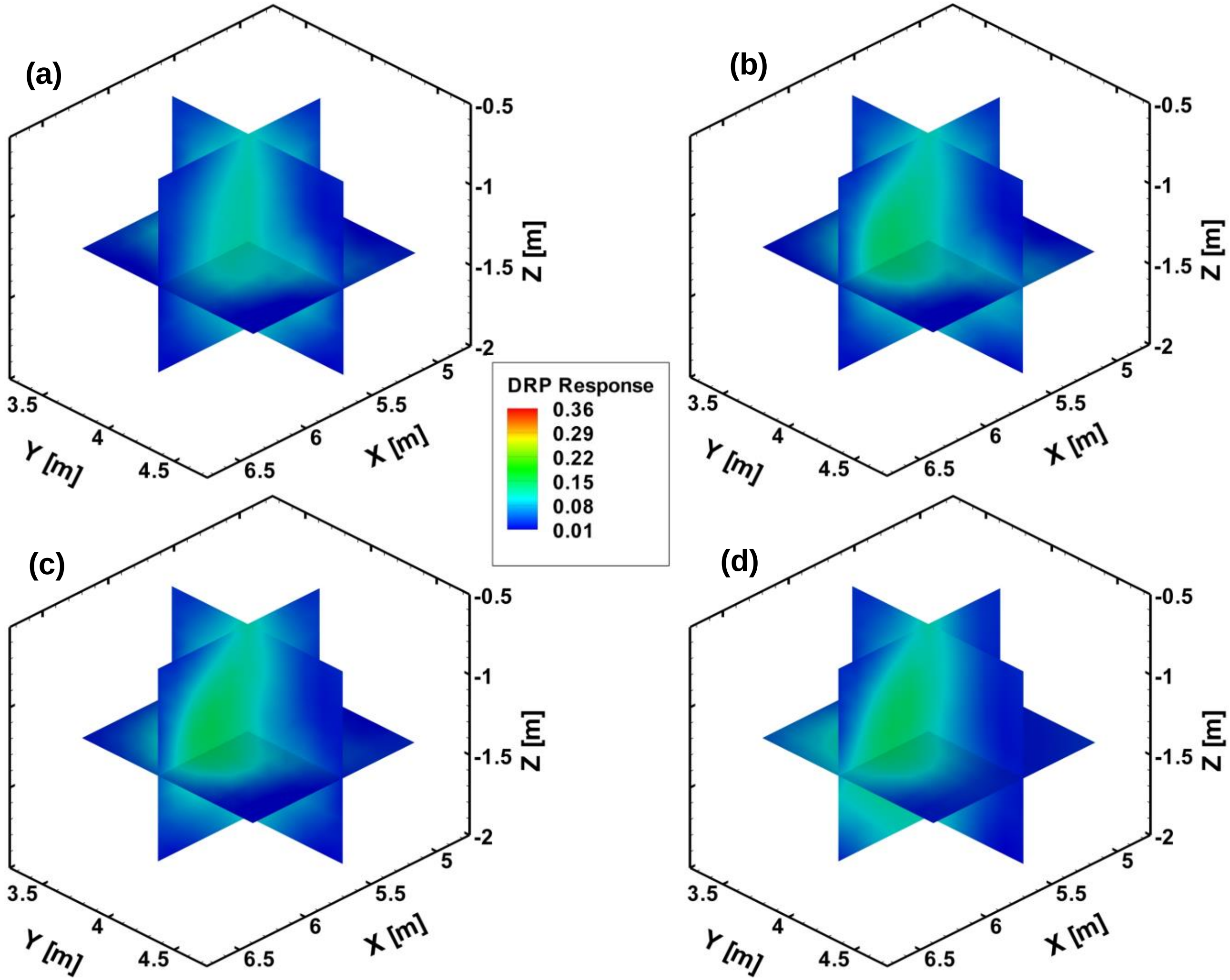




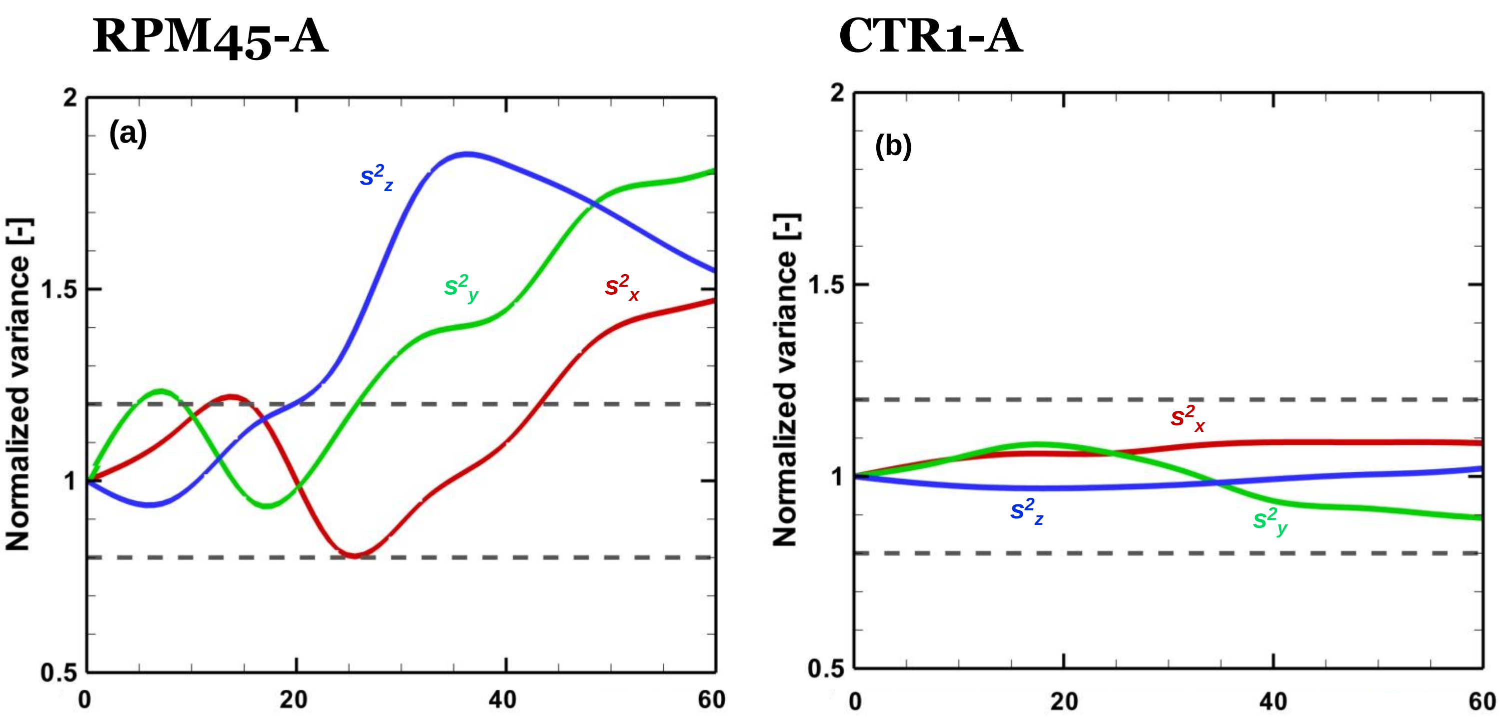
Key Results: Contours (RPM45-A)



Key Results: Contours (CTR1-A)



Key Results: Mixing Behavior



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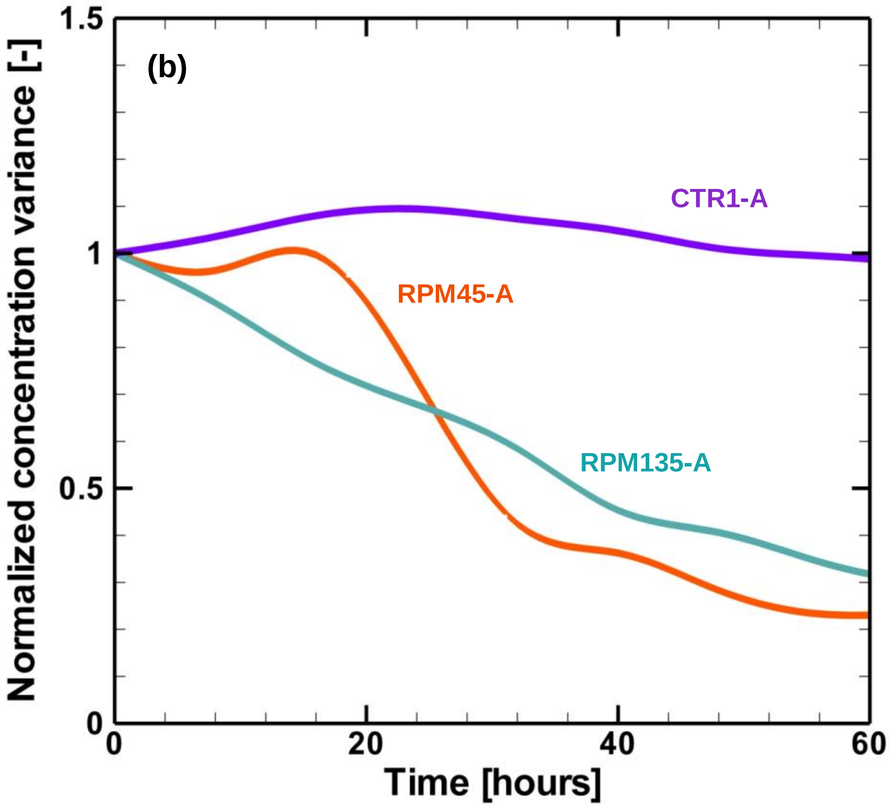
Key Results: Mixing Behavior



Other quantitative metrics used:

- Spatial gradients
- Volume under 3D contours

Summary

- Multiple lines of evidence assembled in this proof-of-concept study demonstrate that an RPM flow system is a viable method for achieving chaotic advection in a porous medium that can significantly enhance reagent delivery

Next Steps

- Additional field investigations:
    - Larger spatial scale
    - Higher K heterogeneity
    - Treatability study with enhanced reagent mixing in a source zone

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Supportive Modeling Work

- Hydraulic tomography analysis using hydraulic data collected from a RPM flow system to generate a *K* field
  - Evaluation of this *K* field in a groundwater flow model to inform the design of a RPM flow system
- Solute transport modeling under chaotic groundwater flow conditions

Groundwater Monitoring&Remediation

Field Trials of Chaotic Advection to Enhance Reagent Delivery

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Abstract

Chaotic advection is a novel approach that has the potential to enhance contact between an injected reagent and target contaminants, and thereby improve the effectiveness of in situ treatment technologies. One configuration that is capable of generating chaotic advection is termed the rotated potential mixing (RPM) flow. A conventional RPM flow system involves periodically reoriented dipole flow driven by transient switching of pressures at a series of radial wells. To determine whether chaotic advection can be engineered using such an RPM flow system, and to assess the consequent impact on the spatial distribution of a conservative tracer, a series of field-scale experiments were conducted. These experiments involved the injection of a tracer in the center of a circular array of wells followed by either mixing using an engineered RPM flow system to invoke chaotic advection, or by natural processes (advection and diffusion) as the control. Pressure fluctuations from the mixing tests using the RPM flow system showed consistent peak amplitudes during injection and extraction at a frequency corresponding to the switching time, suggesting that the target hydraulic behavior was achieved with the time-dependent flow field. The tracer breakthrough responses showed oscillatory behavior at all monitoring locations during the mixing tests which indicated that the desired RPM flow was generated. The presence of chaotic advection was supported by comparisons to observations from a previous laboratory experiment using RPM flow, and the Fourier spectrum of the temporal tracer data. Results from several quantitative metrics adopted to demonstrate field-scale evidence of chaotic advection showed that mixing led to improved lateral tracer spreading and approximately uniform concentrations across the monitoring network. The multiple lines of evidence assembled in this proof-of-concept study conclusively demonstrated that chaotic advection can be engineered at the field scale. This investigation is a critical step in the development of chaotic advection as a viable and efficient approach to enhance reagent delivery.

Introduction

In situ treatment typically involves the injection of a reagent into the subsurface to create a zone in which biological and/or chemical reactions lead to the destruction of contaminants. For example, electron acceptors and/or nutrients are used to create a thriving environment for indigenous microbes to biodegrade organic contaminants (Reinhard et al. 1997; Liebeg and Cutright 1999), while chemical oxidants are injected to destroy or transform a range of contaminants (Siegrist and Simpkin 2016). In either situation, the delivery of the reagent solution is a key requirement for the success of these in situ treatment systems; however, the design of an effective delivery system remains a significant challenge (Kitanidis and McCarty 2012).

Following the injection of a reagent solution into the subsurface, the desired chemical or biological transformations are initiated by transport processes that bring the injected reagent and contaminant together (Kitanidis and McCarty 2012). While this contact between the injected reagent and contaminant is the desired result of an effective delivery system, it can be one of the most difficult to achieve. In relevant literature, it is widely recognized that mixing is distinct to spreading. *Spreading* is associated with the deformation of a reagent plume providing additional opportunities for contact with the contaminant, while *mixing* (or dilution) is a result of various transport mechanisms (e.g., diffusion, sorption/desorption) that cause the reagent and contaminant to overlap leading to a reduction in concentration variance toward a homogenous state (Kitanidis 1994; Jose and Cirpka 2004; Aref et al. 2017). This distinction is particularly important for heterogeneous porous media (Cushman and Tartakovsky 2017). While spreading increases the overall zone of contact between the reagent and contaminant, subsurface heterogeneities create preferential flow pathways over a range of spatial scales (Dagan 1986; Scheibe and Yabusaki 1998) that produce an uneven distribution of the injected reagent fluid. For conventional injection methods that use permanent or temporary vertical wells, the injected reagent will follow the path of least resistance from the wellbore into the porous medium, and the reagent distribution will be greater in areas of higher hydraulic conductivity (K) (Payne et al. 2008). Depending on the permeability contrast, perhaps due to the presence of

Article impact statement: Engineered chaotic advection for enhanced reagent delivery was demonstrated at the field scale.

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QUESTIONS

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