Chaotic Advection Enhanced Remediation

Basic Information

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Publication

1. Bytautas, D., 2006, Enhanced mixing in groundwater remediation, Senior Thesis, Environmental Engineering Program, University of Connecticut, Storrs, CT, pp. 42.
2. Bagtzoglou, A.C., and P. Oates, 2006, On the Enhanced Groundwater Remediation Potential of Chaotic Advection, ASCE Journal of Materials in Civil Engineering, (in press).
3. Bagtzoglou, A.C., N. Assaf-Anid, and R. Chevray, 2006, Effect of Chaotic Mixing on Enhanced Biological Growth and Implications for Wastewater Treatment: A Test Case with Saccharomyces Cerevisiae, Journal of Hazardous Materials (in press, published online).
4. Bagtzoglou, A.C., 2005, Chaotic Mixing and Enhanced Biological Growth: Implications for Wastewater Treatment, Proceedings of International Material Research Congress, Symposium on Ecomaterials, p. 17/4-5.
5. Bagtzoglou, A.C., P. Oates, and E. Loehmann, 2004, Chaotic Advection Enhanced Remediation, Proceedings of AWRA 2004 Annual Water Resources Conference, Nix, S.J. (Editor), American Water Resources Association, Middleburg, Virginia, TPS-04-3, CD-ROM.

PROJECT TITLE: Chaotic Advection Enhanced Remediation (CAEREM)

STATEMENT OF CRITICAL REGIONAL OR STATE NEED

Water is the most ubiquitous biological compound and is imperative to life. As the world's population continues to grow, the demand for fresh water will continue to increase. Out of the 1% of freshwater available on Earth (excluding brackish water and icecaps/glaciers), 96% is in the form of groundwater. Groundwater accounts for about half of the US population's source of drinking water and this number jumps to 95% when focusing on the rural US. However, quantity is not the only problem; the quality of drinking water is also a concern since this vital resource is vulnerable to contamination. In addition to affecting human health, pollution is also detrimental to natural resources and ecosystems with groundwater contamination threatening our society since industrial, municipal, agricultural, and domestic sources pollute the groundwater that many species ultimately rely on. Studies have linked contaminated groundwater to cancer, fetal abnormalities, birth defects, immunodysfunction, and neurological disorders. In 1994, the National Academy of Sciences estimated that over a trillion dollars, or approximately $4,000 per person in the U.S., would be spent in the next thirty years on clean up of contaminated soil and groundwater. Cost effective and time efficient technologies are, therefore, needed to remediate groundwater.

STATEMENT OF RESULTS AND BENEFITS

Groundwater remediation requires cost effective and time efficient technologies. Recent developments in the field of chaotic advection in low Reynolds number flows have led to the belief that a system of oscillating wells (vis-à-vis injection or withdrawal with time-dependent, randomly constrained flow rates) could cause substantial mixing in an aquifer. This could have profound remedial effects when combined with the advection and dispersion, sorption, and biodegradation aspects of natural attenuation. Chaotic groundwater flow would optimize mixing and allow the processes of natural attenuation to occur much faster.

It is hypothesized that the accelerated mixing provided by chaotic advection will enhance the remedial aspects of natural attenuation. This *in situ* technique treats pollution at its source converting contaminants into carbon dioxide, water, and new cellular mass. Chaotic Advection Enhanced REMediation (CAEREM) could possibly turn decades into years, while reducing both exposure risk and clean up costs. Indigenous microbial nutrients and electron acceptors would spread evenly throughout the contaminant plume to accelerate microbial growth. In addition, wells in the injection phase would allow the engineer to insert specific limiting nutrients, electron acceptors, and even genetically engineered microbes, if so desired (and approved). Removal of limiting factors would allow unhindered microbial growth, and the aquifer would be optimized for biodegradation. It is theorized that there will be temporal and economic advantages in utilizing this technology compared to current remedial approaches. In this research work, we propose to use flow and transport modeling to study the mixing phenomena created in groundwater by oscillating wells. To quantify mixing, an index will be developed using the concept of average inter-particle distances and compared with the dilution index, presented in the literature before. Real world practical design considerations will be examined and laboratory-scale experimentation will provide for model testing and verification.

OBJECTIVES OF PROJECT

This two-year effort addresses the following specific objectives:

- Numerically investigate the applicability of CAEREM for confined and unconfined aquifers
- Develop and compare various indices that will allow us to quantify mixing for conservative tracers
- Numerically investigate the sensitivity of CAEREM to ambient groundwater flows
- Extend the method for 3D flow systems (particular emphasis will be placed on making the active screen depth a design parameter thereby enhancing vertical mixing)
- Design and conduct a medium-scale physical laboratory experiment to demonstrate the practical feasibility of CAEREM and facilitate verification and testing of the method

METHODOLOGY

Numerical models were developed to test the scientific hypothesis that oscillating wells could create substantial mixing in an aquifer. Mathematical tools were developed and applied to quantify both mixing and dilution. It has been suggested that using a system of three oscillating wells could enhance mixing. However, relatively recent theoretical work by Sposito and co-workers at UC Berkeley has questioned whether chaotic streamlines are possible for groundwater flows governed by Darcy's law. Additional, external physical conditions must be invoked in order to induce such chaotic streamlines. To accomplish this, our conceptual model calls for all three wells to be connected by pipes and a manhole (all connections must be below the ground surface for regulatory reasons). This allows such external physical conditions to prevail and mass balance to be conserved so no net water is ultimately removed from or added to the aquifer. To enhance the onset of chaos, the system is made as random as possible. One of the three wells is randomly assigned a random pumping magnitude, within realistic constraints, and a random direction (injection or withdrawal). This magnitude is then randomly partitioned to the other wells, which are assigned the opposite flow direction of the first well. This ensures that mass balance is conserved while maximizing randomness. A conceptual model of this system is depicted in Figure 1.

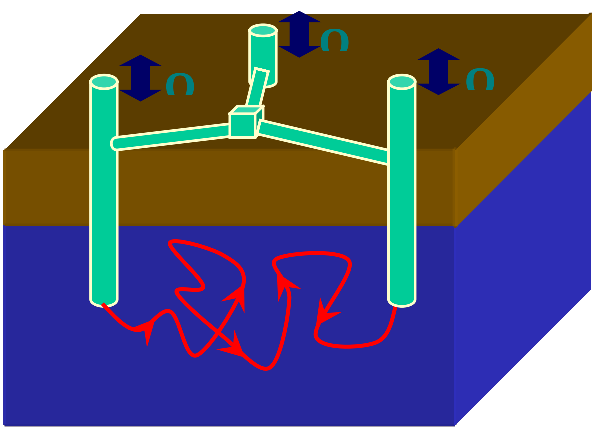
Figure 1. Proposed system

To help quantify the degree of mixing, an index was developed by calculating average inter-particle distances (AIPD). Consider a particular plume (contaminant or nutrients). The average, intra-plume inter-particle distance (*Dg*) for this plume (e.g., nutrients) with particle coordinates *xg* and *yg* is found by calculating the average distance from every particle to every other particle and dividing by the total number of particles. The same analogy can be made for any other plume (e.g., contaminants) with particle coordinates *xr* and *yr*, whose variable will be designated as *Dr*. Since the AIPD of a plume measures the spread of the plume, it is related to the particle cloud variance. It should be noted, however, that the second moment of the particle cloud is not suitable to characterize chaotic advection, since it is insensitive to repeated stretching and folding processes. It is speculated that as these particles mix the AIPD between the contaminant and nutrient plumes (*Dgr*) should decrease. To calculate this value, the contaminant particles look across to the nutrient particles, instead of looking to particles of the same plume.

It is theorized that as the particles become mixed the three AIPDs, *Dg*, *Dr*, and *Dgr* should converge to the same value. Repeated trials have shown that these values indeed converge as the particles become mixed but there is a great deal of erratic oscillation. When mixing causes the average of *Dg* and *Dr* to approach the value of *Dgr*, it is an indication of small-scale convergence. To help reduce this fluctuation, a variable for AIPD of all the particles (*Dg+r*) is introduced. Here, all particles (contaminant and nutrient), *ngr*, are treated as one plume. The information contained in *Dgr* and *Dg+r* should reveal whether the system is mixed or not. However, there should be less erratic fluctuation because *Dg+r* uses a large-scale, as opposed to small-scale, averaging. First, one has to determine when the system starts mixing. To accomplish this we have developing a concept of mixing based on overlapping circles. When there exists a certain particle overlap between the two plumes, mixing is initiated and calculation of percent mixing as a function of time is based on the ratio of these AIPDs as they evolve in time.

CURRENT EFFORTS

We have built a box (Figure 2) that will allow us to formulate a combination of experimental set-ups in which various flow scenarios will be tested. We have provided for the box to be split in two compartments so there exist three wells in each. We are currently instrumenting the box. This system, in which the sensors will be logged using a data acquisition system (DAS), can be controlled by the LabVIEW software. The experimental set-up consists of a number of different sensors: piezometer probes, ion selective electrodes, a DAS and a control and storage computer. The sensors output an analog signal, which is sampled and measured appropriately with the DAS. It will be controlled through the LabVIEW software, which will be running the pump control system and the sensor triggering system. To demonstrate mixing we intend to use two plumes — *NaCl* and *NaBr* — and measure *Cl* and *Br* ions with the help of selective ion electrodes. The large number of probes requires the use of a corresponding number of analog input channels or a multiplex system. For economical and practical reasons we opted for a multiplexed system. We have also designed and are currently building 2 hele-shaw type of thin boxes (less than a meter by a meter) where we will be able to visualize the complex flow patterns developing in these experiments.

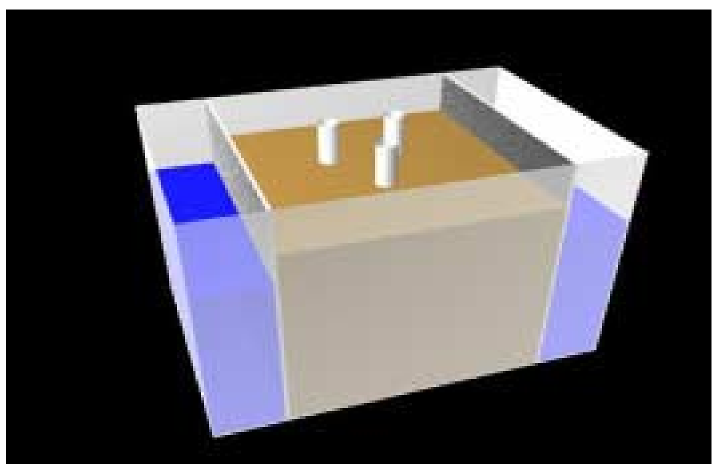

Figure 2. Schematic of experimental facility

FINDINGS TO DATE

Our work to date has culminated to two publications. The first publication – Bagtzoglou, A.C., and P. Oates, 2005, "On the Enhanced Groundwater Remediation Potential of Chaotic Advection", *ASCE Journal of Materials in Civil Engineering* (in press) – can be summarized as follows.

Numerical experiments performed, verified that three randomly oscillating wells, connected through a re-circulation system, can produce substantial mixing. The mixing index developed proved a useful tool when combined with the preexisting dilution index to evaluate this novel technology when tested for realistic remediation parameters. Even though pump and treat has been the remediation method of choice for the past several decades, recent studies have shown many common contaminants become trapped in the subsurface making necessary pumping of extremely large volumes of water over long time periods. It is speculated that CAEREM could take a few years when compared to the several decades of pump and treat. CAEREM could have economic advantages as well; a rough estimate developed with the help of a practicing remediation company suggests that CAEREM could cost around half of pump and treat. Factors contributing to cost reduction include reduced time for site monitoring, reporting, and management, as well as reduced need for maintenance, labor, and supplies. However, it needs to be made clear that this technology is not a "silver bullet" that would be the best choice for every situation. In many cases, the optimal choice may be to combine CAEREM with other technologies.

The second publication – Bagtzoglou, A.C., N. Assaf-Anid, and R. Chevray, 2005, "Effect of Chaotic Mixing on Enhanced Biological Growth and Implications for Wastewater Treatment: A Test Case with *Saccharomyces Cerevisiae*", *Journal of Hazardous Materials* (accepted) – can be summarized as follows.

Mixing patterns and modes have a great influence on the efficiency of biological treatment systems. A series of laboratory experiments was conducted with a controlled, small-scale analog of a pilot wastewater aeration tank, consisting of two eccentrically placed cylinders. By controlling the rotation direction and speed of the two cylinders it has been possible to develop chaotic flow fields in the space between the walls of the cylinders. Our experiments utilized *Saccharomyces Cerevisiae* as the biological oxidation organism and air bubbles as the mixing agent supplied by a large fine pore diffuser to the cells in their exponential growth phase. The effect of various mixing patterns on cell growth was studied at different cylinder eccentricities, rotation directions and speeds. It was found that chaotic advection flow patterns a) enhanced growth, and b) sped up the onset of maximal growth of the organism by 15-18% and 14-20%, respectively.