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Chaotic-Dynamical Conceptual Model to Describe Fluid Flow and Contaminant Transport in a Fractured Vadose Zone

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Research Objective

DOE faces the remediation of numerous contaminated sites, such as those at Hanford, INEEL, LLNL, and LBNL, where organic and/or radioactive wastes were intentionally or accidentally released to the vadose zone from surface spills, underground tanks, cribs, shallow ponds, and deep wells. Migration of these contaminants through the vadose zone has lead to the contamination of or threatens to contaminate underlying groundwater. A key issue in choosing a corrective action plan to clean up contaminated sites is to determine the location, total mass, mobility and travel time to receptors for contaminants moving in the vadose zone. These problems are difficult to solve in a technically defensible and accurate manner because contaminants travel downward intermittently through narrow pathways driven by variations in environmental conditions. These preferential pathways can be difficult to find and predict.

The primary objective of this project is to determine if and when dynamical chaos theory can be used to investigate infiltration of fluid and contaminant transport in heterogeneous soils and fractured rocks. The objective of this project is being achieved through the following Activities

1) Evaluation of chaotic behavior of flow in laboratory and field experiments using methods from non-linear dynamics;
2) Evaluation of the impact these dynamics may have on contaminant transport through heterogeneous fractured rocks and soils, and how it can be used to guide remediation efforts;
3) Development of a conceptual model and mathematical and numerical algorithms for flow and transport, which incorporate both: (a) the spatial variability of heterogeneous porous and fractured media, and (b) the description of the temporal dynamics of flow and transport, which may be chaotic; and
4) Development of appropriate experimental field and laboratory techniques needed to detect diagnostic parameters for chaotic behavior of flow.

This approach is based on the assumption that spatial heterogeneity and flow phenomena are affected by non-linear dynamics, and in particular, chaotic processes. The scientific and practical value of this approach is that we can predict the range within which the parameters of flow and transport change with time in order to design and manage the remediation, even when we can not predict the behavior at any point or time.

Research Progress and Implications

This progress report summarizes work after 1.5 years of a 3-year project.

Ponded infiltration tests were conducted in Idaho at two fractured rock field sites: the Hell's Half Acre (the scale of 1 by 0.5 m) and the Box Canyon (the scale of 7 by 8 m) sites. Using monitoring of water movement at drip points, geophysical imaging, in-situ measurements of the moisture content, water flow rate, water pressure in the rock matrix and fractures, subsurface tracer distribution, and other critical parameters, the temporal and spatial evolution of unsaturated flow in fractured rock were characterized for the first time in fractured basalt. Several new technologies have been developed specifically for this project including piezoelectric probes, a leak detection system, a laser surveying system, and a 3D Electrical Resistivity Tomography system.

Laboratory experiments were conducted to evaluate the presence of chaotic behavior in water seepage through fracture models, which have shown the pervasiveness of highly localized and extremely non-uniform flow paths in the plane of the fracture. Using the time-trend of a pressure signal for unsaturated flow in fracture models, the magnitude of deterministic-chaotic and stochastic components in the data were analyzed. For this purpose, several parameters were determined such as Hurst exponent, Lyapunov exponent, capacity dimension, correlation dimension, information dimension, correlation time, and constructed two-dimensional and three-dimensional attractors in phase-space.

Numerical modeling of the Box Canyon ponded infiltration tests using the TOUGH2 code with an explicit, yet simplified, representation of the key geologic and hydrogeological features (a hierarchical pattern of column-bounding and column-normal fractures in fractured basalt) confirmed: (a) the presence of complex, irregular flow paths for liquid-phase tracer, as well as air trapping and escaping in the vadose zone, and (b) the temporal aspects of chaotic flow, identified in laboratory and field experiments, cannot be captured using conventional modeling approaches.

Theoretical studies have shown that as a fluid film flows vertically on a fracture surface, it is inherently unstable and may exhibit chaotic behavior, even for low Reynold's numbers. Film waviness may enhance transfer of contaminants from rock to fluid by as much as five times carrying contaminated fluid down a fracture much faster than expected by classical flat film theory.

The scientific significance of the research rests in: (a) the unique non-linear dynamics analysis of data sets such as fracture and matrix flow rates, pressure, and tracer concentrations, and (b) the development of a new dynamical chaotic model for flow and transport in fractured media. The results of this project are expected to change the conventional approach of using traditional stochastic and/or deterministic methods to predict flow and transport in environmental systems. Because the non-linearity of environmental systems limits their predictability into the future, we aim to determine how far into the future it is realistic to predict the state of the environmental system, and what the bounds on the time of contaminant transport are, and how long we can expect clean-up to take. The significance of the research for the DOE will be in the form of technology developed for vadose zone monitoring and in improved vadose zone site characterization and predictability.

Planned Activities

Additional field and laboratory experiments will be conducted in 1998 to examine the fracture/matrix interactions. Analysis of existing data from DOE sites (INEEL, LBNL, LLNL, and other) will be provided in 1998-99. Reports and publications will be written and made available to the environmental community at large. The methodology developed will be recommended to DOE sites where monitoring and remediation of contaminants using vacuum extraction, air stripping, steam injection, barriers, etc. are problems.

Other Access To Information

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