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BARD

FINAL REPORT

PROJECT NO. IS-2859-97

**Characterization of Preferential Flow in Spatially
Variable Unsaturated Field Soils**

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Project Title: CHARACTERIZATION OF PREFERENTIAL FLOW IN SPATIALLY
VARIABLE UNSATURATED FIELD SOILS

Investigators

Principal Investigator (PI): David Russo

Co-Principal Investigator (Co-PI): William A. Jury

Collaborating Investigators:

Institutions

ARO Israel

UCR, USA

Keywords *not* appearing in the title and in order of importance. Avoid abbreviations.

Abbreviations commonly used in the report, in alphabetical order

Budget: IS: \$88,000

US: \$121,000

Total: \$209,000

Signature
Principal Investigator

Signature
Authorizing Official, Principal Institution

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Publication Summary (numbers)

	Joint IS/US authorship	US Authors only	Israeli Authors only	Total
Refereed (published, in press, accepted)		2	2	4
Submitted, in review, in preparation				
Invited review papers				
Book chapters				
Books				
Master theses				
Ph.D. theses				
Abstracts				
Not refereed (proceedings, reports, etc.)		2	1	3

Postdoctoral Training: List the names and social security/identity numbers of all postdocs who received more than 50% of their funding by the grant.

Dr. Zhi Wang, UCR employment, ID 855629654

Cooperation Summary (numbers)

	From US to Israel	From Israel to US	Together, elsewhere	Total
Short Visits & Meetings		1	1	2
Longer Visits (Sabbaticals)				

Description of Cooperation:

The US team concentrated on tasks under objective 1, while the Israeli team concentrated on tasks under objectives 2 and 3. Information exchange was performed via electronic mail, visit (Riverside), and meeting (Monte Verita). The data base from the US experiments was shared and the results were pooled into a comprehensive analysis of the phenomenon.

Patent Summary (numbers)

	Israeli inventor (s) only	US inventor (s) only	Joint IS/US inventors	Total
Submitted				
Issued (allowed)				
Licensed				

Abstract

Preferential flow appears to be the rule rather than the exception in field soils and should be considered in the quantitative description of solute transport in the unsaturated zone of heterogeneous formations on the field scale. This study focused on both experimental monitoring and computer simulations to identify important features of preferential flow in the natural environment.

The specific objectives of this research were: (1) To conduct dye tracing and multiple tracer experiments on undisturbed field plots to reveal information about the flow velocity, spatial prevalence, and time evolution of a preferential flow event; (2) To conduct numerical experiments to determine (i) whether preferential flow observations are consistent with the Richards flow equation; and (ii) whether volume averaging over a domain experiencing preferential flow is possible; (3) To develop a stochastic or a transfer function model that incorporates preferential flow.

Regarding our field work, we succeeded to develop a new method for detecting flow patterns faithfully representing the movement of water flow paths in structured and non-structured soils. The method which is based on application of ammonium carbonate was tested in a laboratory study. Its use to detect preferential flow was also illustrated in a field experiment. It was shown that ammonium carbonate is a more conservative tracer of the water front than the popular Brilliant Blue. In our detailed field experiments we also succeeded to document the occurrence of preferential flow during soil water redistribution following the cessation of precipitation in several structureless field soils. Symptoms of the unstable flow observed included vertical fingers 20 - 60 cm wide, isolated patches, and highly concentrated areas of the tracers in the transmission zone. Soil moisture and tracer measurements revealed that the redistribution flow became fingered following a reversal of matric potential gradient within the wetted area.

Regarding our simulation work, we succeeded to develop, implement and test a finite-difference, numerical scheme for solving the equations governing flow and transport in three-dimensional, heterogeneous, bimodal, flow domains with highly contrasting soil materials. Results of our simulations demonstrated that under steady-state flow conditions, the embedded clay lenses (with very low conductivity) in bimodal formations may induce preferential flow, and, consequently, may enhance considerably both the solute spreading and the skewing of the solute breakthrough curves. On the other hand, under transient flow conditions associated with substantial redistribution periods with diminishing water saturation, the effect of the embedded clay lenses on the flow and the transport might diminish substantially.

Regarding our stochastic modeling effort, we succeeded to develop a theoretical framework for flow and transport in bimodal, heterogeneous, unsaturated formations, based on a stochastic continuum presentation of the flow and a general Lagrangian description of the transport. Results of our analysis show that, generally, a bimodal distribution of the formation properties, characterized by a relatively complex spatial correlation structure, contributes to the variability in water velocity and, consequently, may considerably enhance solute spreading. This applies especially in formations in which: (i) the correlation length scales and the variances of the soil properties associated with the embedded soil are much larger than those of the background soil; (ii) the contrast between mean properties of the two subdomains is large; (iii) mean water saturation is relatively small; and (iv) the volume fraction of the flow domain occupied by the embedded soil is relatively large.

Achievements

Significance of Results

We were able to meet all of our goals in this BARD project, as articulated in the project proposal objectives. In this section we discuss the significance of our results relative to the original expectations. The US investigators spent a considerable effort developing and testing a novel method for detecting flow patterns faithfully representing the movement of water flow paths in structured and non-structured soils. The method is based on application of ammonium carbonate during infiltration, which displays a unique color signature when sprayed with a pH indicator after excavation and exposure of the soil profile along a trench face. The performance of the method was compared to that of the popular Brilliant Blue in a laboratory study, and show that it is a more conservative tracer of the water front. The US investigators also succeeded to illustrate the use of the new method in a field experiment to detect preferential flow. In contrast to other methods, the ammonium carbonate used in the new method, is inexpensive, nontoxic and leaves negligible residue.

A major effort (18 field experiments) was put forth in the US in order to quantify the effects of redistribution on preferential flow in structureless soils. The US investigators succeeded to document the occurrence of preferential flow during soil water redistribution following the cessation of precipitation in several structureless field soils. The major achievement of this effort is that the US investigators succeeded to provide experimental evidence which supports the hypothesis that a reversal of the matric potential gradient during redistribution of soil water following infiltration in a structureless soils may cause preferential flow by inducing a fluid instability at the leading edge of the wetting front.

The Israeli investigators constructed a realistic, three-dimensional simulation model of water and solute movement in a bimodal, heterogeneous, partially saturated medium with highly contrasting soil materials. The approach taken provide detailed information on the consequences of spatial heterogeneity of the soil properties for the transport of solutes under quite realistic conditions. Such information cannot, in general, be obtained in practice from field investigations. For example, the clay lenses which considerably affect the flow and the transport under steady-state flow conditions, occupy less than 10% of the medium volume. This finding has important implications inasmuch as in practice, less than optimal selection of the locations of the observation points, an insufficient number of observation points, and

measurement errors may lead to an inadequate characterization of the spatial structure of the relevant medium properties. Consequently, in the case in which the clay lenses occupy only a small fraction of the medium volume, the "true" underlying bimodal distribution of the medium properties may be incorrectly viewed as a unimodal distribution.

Another important finding of the numerical effort is that under steady-state flow conditions, embedded clay lenses (with very low conductivity) in bimodal formations may induce preferential flow, and, consequently, may enhance considerably both the solute spreading and the skewing of the solute breakthrough curves. On the other hand, under more realistic, transient flow conditions associated with substantial redistribution periods with diminishing water saturation, the effect of the embedded clay lenses on the flow and the transport might diminish substantially.

The Israeli investigators concentrated also on analyzing flow and transport in bimodal, heterogeneous, unsaturated formations, based on a stochastic continuum presentation of the flow and a general Lagrangian description of the transport. One of the major findings of this effort is the important role played by the formation parameter, α under unsaturated flow conditions. Consequently, the macrodispersion in a bimodal, unsaturated formation may be larger than its counterpart in a saturated formation, especially when the degree of saturation decreases; when the volume fraction of the flow domain occupied by the embedded soil increases; when the disparity between the correlation length scales of the two subdomains is relatively small; and when the texture of the embedded soil is coarser than that of the background soil.

Cooperation

Although the main emphasis of the US group was physical experimentation and that of the Israeli group numerical and stochastic modeling, the two groups conducted their research from a common design scheme that produced different perspectives on common problems. Water flow and solute transport on the field scale are of sufficient complexity that current methods are often found lacking in representing these processes under natural conditions. Our research was designed to create new tools for addressing the problems created by preferential flow on the field scale, for which we designed both an experimental and theoretical attack. Wherever possible, US and Israeli investigators used complementary approaches to the same problem to maximize the effectiveness of the investigation. For example, the US investigators

concentrated on the situation in which a reversal of the matric potential gradient during redistribution of soil water following infiltration in a structureless soils may cause preferential flow by inducing a fluid instability at the leading edge of the wetting front. On the other hand, the Israeli investigators concentrated on the situation in which interbedded lenses of fine-grained, low conductivity soil material may induce preferential flow.

List of publications

1. Russo, D., 2001. Stochastic analysis of macrodispersion in bimodal heterogeneous variably saturated porous formations. Water Resour. Res. (in review).
2. Russo, D., J. Zaidel, and A. Laufer, 2001. Numerical analysis of flow and transport in a variably saturated bimodal heterogeneous porous formation. Water Resour. Res. 37: 2127-2141.
3. Wang, Z., L. Wu, T. Harter, J. Lu, and W. A. Jury, 2001. A field study of preferential flow during soil water distribution. Water Resour. Res. (in review).
4. Wang, Z., L. Wu, J. Lu, T. Harter, and W. A. Jury, 2001. Visualizing preferential flow paths using ammonium carbonate and a pH-indicator. Soil Sci. Soc. Am. J. 65: (in press).