TRIP REPORT

SUBJECT: International Workshop on Field Scale Water and Solute Flux in Soils

DATE AND PLACE: September 24-29, 1989
Monte-Verita
Ascona, Switzerland

AUTHOR: Rachid Ababou

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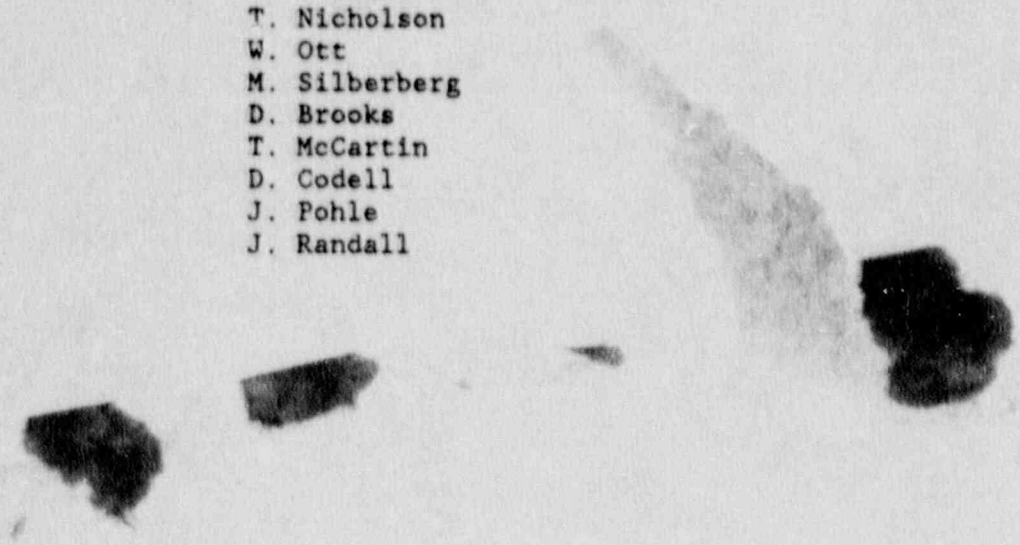

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SUBJECT: International Workshop on Field Scale Water and Solute Flux in Soils

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PERSON PRESENT: CNWRA

Rachid Ababou

BACKGROUND AND PURPOSE OF TRIP:

The Swiss Federal Institute of Technology (ETH) of Zurich, Switzerland, organized the International Workshop on "Field Scale Water and Solute Flux in Soils" held last week at the Monte-Verita Conference Center in Ascona, Switzerland (September 24-29, 1989). About 60 researchers including R. Ababou attended the meeting, mostly from Europe and North America. The workshop activities consisted of research presentations, "think tank" sessions, and a one-day field trip. A brief overview of the meeting is given below.

SUMMARY OF PERTINENT POINTS:

About 35 invited presentations were given over a period of four days. A list of abstracts is attached and some papers, distributed at the conference, are also available upon request. Some of the presentations may eventually be published in a book (proceedings) to be produced by Birkhauser Publishers. R. Ababou's presentation on the "Space-Time Structure of Unsaturated Flow in Heterogeneous and Stratified Media" was essentially an overview of stochastic concepts and their possible applications to characterize complex unsaturated flow processes. This was illustrated by some of R. Ababou's previous work on stochastic/ numerical flow modeling, to be published elsewhere.

The 60 workshop attendees were split into four working groups, or "think tanks." The think tank sessions were held every day in order to discuss and identify specific areas of research. R. Ababou participated in Think Tank No. 1 on "Effective Large-Scale Unsaturated Flow and Transport Properties." Documentation on think tank activities is available in the form of informal notes generated collectively during the sessions.

In addition, there was a one-day field trip to the underground Grimsel test site operated by NAGRA, the Swiss federal agency in charge of the nuclear waste disposal program (National Cooperative for the Storage of Radioactive Waste). Some documentation on this is enclosed and more information is available upon request. More details on workshop activities, including

research presentations, "think tanks," field trip, information about the Swiss disposal program, and personal contacts are given below.

SUMMARY OF ACTIVITIES:

Research Presentations:

As mentioned above, my presentation at the workshop was a fairly broad overview of unsaturated flow processes from a modeling perspective, starting with relatively simple systems and ending with fairly complex ones (heterogeneities, stratification, transients, etc.). Results of large scale three-dimensional numerical experiments were shown.

A number of other researchers presented new results, interpretations, and models related to three-dimensional field scale experiments in unsaturated soils. Some notable contributions in this area were:

- Pete Wierenga's second strip source flow and tracer "trench experiment" near Las Cruces, New Mexico; the typical scale of this 3D experiment is 10 m in each direction.

- Greg Butters, et al. one-dimensional tracer recovery experiment up to depths of 15 m, and some new 3D data related to that experiment.

- R. Kachanovski, et al. field tracer experiment of the University of Guelph, in Southern Ontario, Canada, with extremely variable soil horizon thickness; the vertical scale is small, about 2 meters.

- Los Alamos flow and tracer "caisson experiments" in 6 meter deep columns containing crushed Bandelier tuff; this essentially 1D experiment was reinterpreted by Nguyen and Dagan using a simplified stochastic travel time model.

- Kurt Roth (ETH Zurich) unsaturated tracer experiment was monitored from a 12 m long, 3 m deep tunnel; the tracer plume split in two parts, a slow moving part and a fast moving part. He interpreted his results using a particle tracking model with advection and diffusion on a "double-porosity continuum structure." Kurt Roth and his advisor, Hannes Fluhler, were the principal organizers of the workshop.

- Fritz Stauffer, et al., presented ongoing field measurements of hydrodynamic properties in fluvial sand-and-gravel deposits near Zurich, Switzerland. Particle size distributions were distinctly bi-modal.

- There were other interesting contributions on interpretations of field experiments, notably by Lynn Gelhar, Bill Jury, and others.

There were virtually no presentations on experimental approaches to unsaturated flow in fractured rocks per se, apart from the modeling study presented by Budi Sagar. However, many contributors did focus on experimental and modeling approaches for soils with macropores and cracks. See for example

the above-mentioned field experiment of Kurt Roth, and the watershed-scale subsurface flow experiment of Bob Luxmoore at Oak Ridge. Interpretation of the latter in terms of percolation theory is still at a preliminary stage. Finally, it should be noted that one of the "think tanks" was entirely devoted to preferential flow phenomena in soils. The hydrodynamic problems are somewhat similar to those encountered with fractured rocks.

Think Tanks:

Four "think tank" sessions were held. The titles of the sessions and names of the discussion leaders are given below. Some documentation on think tank activities, particularly Think Tank No. 1, are available from R. Ababou upon request.

Think Tank 1: Use and Limitations of Effective Large Scale Unsaturated Flow Properties in Numerical Models (Lynn Gelhar, MIT, and Jack Parker, Virginia Polytechnic Institute).

Think Tank 2: Flow and Transport Modeling Approaches: Philosophy, Complexity, and Relationship to Measurements (Hannes Fluhler, ETH Zurich, and Anders Rasmuson, KEMAKTA Stockholm).

Think Tank 3: Evaluation of Field Properties from Point Measurements (Magdi Selim, Louisiana State University, and Rainer Schulin, ETH Zurich).

Think Tank 4: Evaluating the Role of Preferential Flow on Solute Transport through Unsaturated Field Soils (Bill Jury and Kurt Roth, ETH Zurich).

Field Trip:

The field trip was as interesting as announced by the organizers. The activities are listed below.

- Four of the highest passes in the Alps, and some of the longest road tunnels was traversed.
- The inside of a glacier was inspected.
- One of the Obershali hydroelectric plants, part of a complex system of interconnected reservoirs in the Swiss Alps was visited.
- The Grimsel Laboratory 500 meters below-ground in fractured granite rock was observed.
- We saw one of the largest accessible quartz crystal group.

The most notable part of the field trip was the visit of the underground Grimsel Laboratory, guided by Peter Hulshmiedt of NAGRA. The Grimsel is a test site operated by the Swiss National Cooperative for the Storage of Radioactive Waste, known as NAGRA by its German acronym or CEDRA by its French acronym. Pages 2-3 of the NAGRA Bulletin, 1988 edition, which summarizes some of their ongoing experiments at the Grimsel site are attached. The full NAGRA

Bulletin will be circulated at the Center and can be consulted upon request to R. Ababou. Some notable features about the Swiss High-Level Waste Disposal Program, NAGRA, and the Grimsel test site are indicated below.

Swiss High-Level Waste Disposal Program:

What follows is a highly subjective and incomplete summary of what was gathered concerning the Swiss High-Level Waste Disposal Program, Project "Gewahr." This project, led by NAGRA, was initially based on the concept of a repository in the deep-lying crystalline bedrock of Northern Switzerland near the German border. However, based on observations from seven deep boreholes, the bedrock was found to lie much deeper than expected. There is a deep bedrock trough (3-6 km deep) over most of the candidate repository site. Other options are now being considered, particularly sites in clay sediments and in molasses, to be investigated from 1989 through 1993. The goal of this newly extended program is to come up with a new candidate site and start conducting site specific characterization by 1995. These new developments, are not mentioned in the 1988 NAGRA Bulletin.

In view of the new uncertainty concerning the future candidate repository in Switzerland, it seems that some of the hydraulic and tracer tests at the Grimsel site will have to be diversified. The guide at the Grimsel site, Peter Hufshmiedt, paid particular attention to unsaturated flow processes at the tunnel wall (ventilation test described in the 1988 NAGRA Bulletin). It appears that increasing the dry air ventilation rate resulted in higher inflow from the tunnel walls, as measured by the delivery of condensed water on a cooling trap.

IMPRESSIONS/CONCLUSIONS:

The workshop was quite successful, in my opinion, as a forum for scientific debate. A number of experimental results on unsaturated media are now becoming available for purposes of model validation.

I contacted a number of persons at the workshop, for exchange of data, discussion of scientific information, and in certain cases for coordination of research work. Among the NRC contractors contacted at the workshop were Dr. Peter J. Wierenga (Chairman, Department of Agricultural Engineering, University of Arizona, Tucson, Arizona) and Dr. Lynn W. Gelhar (Department of Civil Engineering, Massachusetts Institute of Technology, Cambridge, Massachusetts). There were fruitful contacts as well with a number of other researchers from U. S., French, and Swiss institutions.

PROBLEMS ENCOUNTERED:

None

PENDING ACTIONS:

None

RECOMMENDATIONS:

Attendance at such meetings plays an important role in publicizing NRC and CNWRA research efforts as well as obtaining up to date information on recent progress in key areas of research. It is recommended that such communication channels be kept open in the future, notably through research presentations by CNWRA staff at scientific conferences and workshops.

SIGNATURE: Rachid Ababou 10/9/89
Date

REFERENCES:

None

CONCURRENCE SIGNATURE AND DATE:

John Russell 10/9/89
Date

/bsc

Attachments

ABABOU, R.

Southwest Research
Institute
San Antonio, USA

Space-time Structure of Unsaturated flow in heterogeneous and stratified media

Overview of unsaturated flow processes taking place in multi-dimensional, randomly heterogeneous porous media, using analytical models, numerical simulations, and stochastic concepts. Emphasis on space-time structure and statistics of the flow at large scales.

ADDISCOTT, T.M.

Rothamsted Exp. Station
Harpenden, GB

Relating the variability in the parameters of a leaching model to the variability in the percentages of clay and other soil components

Saying that the soil is heterogeneous has several implications. It means that soil contains several components, i.e. clay, sand, silt etc. It also takes note of the aggregated structure of most soils. It also implies that the properties of the soil vary within a site. A leaching model developed at Rothamsted has both capacity and permeability parameters; these are needed because of the structural heterogeneity of the soil. Both parameters can be related empirically to the percentages of clay and other soil components. This paper will explore the extent to which the variability in the percentages of the soil components within a site provides an estimate of the intra-site variability in the parameters of the leaching model. The paper will consider the effects of both the extent of the variability, i.e. the size of the variance, and its spatial structure.

ANKENY, M.D., R. HORTON, AND T.C. KASPAR

Iowa State University
Dept. of Agronomy
Ames, USA

Field estimates of hydraulic conductivity from unconfined infiltration measurements

Soil water infiltration has high spatial variability due to both intrinsic soil properties and management effects (e.g. wheel traffic and tillage). The determination of hydraulic properties of unsaturated soil requires both a rapid field technique to sample the necessary number of sites and a straightforward analytical technique for interpreting data. We have designed precision automated tension infiltrometers which enable rapid determination of soil water infiltration. Tension infiltrometers were used to obtain unsaturated infiltration data for notill fields of wheel trafficked and non-wheel trafficked management zones. This paper reports means and coefficients of variation for unconfined infiltration rates and hydraulic conductivities at multiple tensions. The field hydraulic conductivity values are similar to laboratory measured values on cores taken from the field site. Mean hydraulic conductivity decreased as tension increased. Trafficked sites have lower values of hydraulic conductivity than non-trafficked sites. Coefficients of variation were roughly 40% for cases. The tension infiltrometer is a useful tool for obtaining spatial measurements of field infitration and unsaturated hydraulic conductivity.

BÖTTCHER, J. AND, O. STREBEL

Bundesanstalt für Geowissenschaften und Rohstoffe, Hannover, D

Stochastic and deterministic variability components of groundwater solute concentrations at the water table in sandy soils measured along transects

In a study area in northern Germany groundwater solute concentrations at the water table were measured along transects (30 m long) to gain insight into the spatial variability of non-point solute input from unsaturated sandy soils into groundwater. It was found, that landuse specific extrinsic factors (e.g. fertilization on arable land, solute input from canopy interception of atmospheric constituents and throughfall under coniferous forest) can strongly influence the variability patterns of solute concentrations at the water table. Our paper focuses on separating the variability of solute concentrations at the water table into deterministic (spatially predictable) and stochastic (not predictable) components. Spatial correlations and/or stochastic properties of the variability components are analyzed. The results can be helpful in identifying the influence of fieldscale heterogeneity on solute transport in sandy soils, and in selecting an appropriate sampling strategy for field studies on mean solute concentrations in the groundwater recharge under hectare plots.

BRESLER, E.

Institute of Soils & Water
ARO, The Volcani Center
Bet Dagan, Israel

A distributed parameter stochastic model for an interactive solute transport in unsaturated heterogeneous soil at field scale

The transport of an interactive solute in unsaturated horizontally heterogeneous field soil is investigated. Four solute transport factors and their variability have been examined:

a) connection by vertical velocity, which changes in plane because of variability in soil hydraulic properties;
b) pore scale dispersivity,
c) anion exclusion phenomena; and
d) cation sorption to the soil clay surface.

The field parameters and solute concentration were regarded as random. Closed form equations, requiring only a numerical quadrature were derived for probability distribution of C, using several simplifying assumptions. Detailed statistical information about the interactive solute distribution in the field was calculated and compared with breakthrough data of undisturbed field soil columns.

BUTTERS, G. L., T. R. ELLSWORTH, AND W. A. JURY

Department of Agronomy
Colorado State University
Fort Collins, USA

EXP.

Modeling solute dispersion at the field scale

A recently published one-dimensional tracer recovery experiment in a 0.64 ha loamy sand revealed a nearly linear increase in the longitudinal macrodispersivity to a depth of at least 15 m. Interesting variations in the development of the travel time variance were attributed to observed changes in the soil texture and structures although alternative mechanistic explanations for the perturbations were unresolvable. A subsequent and more detailed three-dimensional study in the same field has partially clarified the role of soil changes in the dispersion process. Current understanding of the influence of soil layers on solute dispersion is

reviewed together with a report on attempts to evaluate the tracer velocity correlation structure from soil properties and flow measurements.

CISLEROVA, M., T. VOGEL AND J. SIMONEK

Dept. of Drainage and Infiltration
Faculty of Civil Engineering
Czech Technical University
Praha, CSSR

A message of ponding infiltration experiments for modeling purposes

For some soils, significant irregularities in the behaviour of soil-water system can take place, often hidden in variability effects. For modeling purposes it is important to know the character of these deviations, since many of them are in contradiction with the theory. To study them, a simple infiltration experiment supplies valuable information.

As an example, the field infiltration process is analyzed on data set obtained in a selected locality; results are discussed together with similar results for other soil types. In each case deviations from the theory are traced. Corresponding space and time variability is discussed using the scaling of cumulative infiltration.

Finally, the prospects of the use of cumulative infiltration experiment for the determination of soil hydraulic characteristics based on the inverse problem solution are studied and documented on examples.

CLOTHIER, B., K. SMETTEN, ** AND P. RAHARDJO ****

*DSIR, N.Z., **CSIRO, Aus., ***TRI, Indonesia

Measuring the saturated and unsaturated properties of field soils

Clearer perception and better modelling of soil water and chemical flow will be aided by improved measurement of the appropriate saturated and unsaturated flow characteristics of field soil, especially near, or on the surface. In situ field measurements are presented for two contrasting soils: the herbicided soil of an apple orchard, and a soil growing pasture. These data are combined with more unsaturated results from analysis on undisturbed cores. These results highlight the difficulty in estimating the hydraulic flow properties [$K(\Theta)$ or $D(\Theta)$] by reference to the static $\Psi(\Theta)$ characteristic. The Philip-White-Sully flow-weighted "mean" pore size emphasizes the contrasting infiltration pathways of water and chemical entry through the surface of these soils. Soil water content measurements after sprinkler irrigation verify these conjectures for unsaturated flux infiltration into the orchard soil. Additionally our water extraction observations stress the prime role of surface roots in taking up water and chemical, even in these deep rooting trees.

CVETKOVIC, V. AND G. DESTOUNI

The Royal Institute of TechnologyfStockholm, S

Mass Flux of sorptive solute in heterogeneous soils

A stochastic model for the expected mass arrival of solute that undergoes sorption-desorption governed by first-order linear kinetics in heterogeneous soils, is presented. The expected mass arrival at any distance from the injection point is expressed in terms of the stochastic properties of the fluid velocity field and the forward- and reverse-sorption rate coefficients. The model is applied to evaluate the expected field-scale mass flux of sorptive solute into the groundwater from heterogeneous fields, using the flow model proposed by Bresler and Dagan (1981). The influence of variability in the sorption-desorption rate coefficients that are assumed to be negatively correlated with the hydraulic conductivity at saturation, is illustrated. The spatial variability in the sorption parameters can have a

significant impact on the expected cumulative mass arrival into the groundwater. Using the harmonic mean of the sorption parameters most closely approximates the results generated using variable sorption-desorption coefficients.

DAGAN, G.

Dept. of Fluid Mechanics and Heat Transfer
Faculty of Engineering
Tel Aviv Univ.
Ramat Aviv, Israel

Uncertainty, scales and ergodicity in transport through heterogeneous soils

Uncertainty of prediction of transport of solutes at field scale stems from two sources: spatial variability of soil properties and estimation errors of parameters. Each factor is analysed separately. The various scales influencing the process are analysed and their role in reducing uncertainty is discussed. Ergodicity requirements are examined in terms of these length scales.

GASCUEL-ODOUX, C.

INRA Science du Sol
Rennes, F

Spatial variation of flow processes under unsaturated field conditions: data treatment for the description

Field scale heterogeneity affecting flow processes in the unsaturated zone is studied by two ways: (1) a stochastic approach; soil water movement is described by using an environmental isotope, oxygen 18, as a water movement tracer under field conditions. This method gives facilities about studying in situ water movement without artefacts and with any sampling. Geostatistical data treatments are performed. Spatial correlation structures at different scales - from some meters to some hectares - are compared; relationships to soil characteristics are analyzed on various experimental cases. (2) A deterministic pedological approach, considered as the first step in order to study field scale heterogeneity of flow processes; spatial variation of soil properties are studied on small toposequences which present obvious morphological heterogeneities and might be considered as a representative basis for spatial generalization of flow processes. Geostatistical data treatments are also performed in this way.

GASTON, L.A. AND H.M. SELIM

Louisiana State UniversitycBaton Rouge, USA

Transport of exchangeable cations for binary and ternary

The transport of exchangeable cations for binary and ternary systems in an aggregated Sharkey clay soil using miscible displacement methods was investigated. Pulses of $MgCl_2$ or $MgCl_2$ plus NaCl were applied to uniformly packed soil columns, then eluted with $CaCl_2$. Experimental leaching data were compared to predicted breakthrough curves obtained using the classical (or one-region) and mobile/immobile water (or two-region) transport models. The two-region model offered no improvement over predictions obtained using the one-region model. The locations of all breakthrough peaks were well-described by the models, however, peak heights for Mg breakthroughs were consistently overestimated. Extension of the model to include the occurrence of $CaCl^+$ and $MgCl^+$ and adsorption of these complexes did not improve model predictions.

GELHAR, L.W.

MIT Dept. of Civil Engineering,
Cambridge, USA

Field-scale transport processes in heterogeneous soils

Recent advances in the understanding of large-scale flow and solute transport processes in naturally heterogeneous soil environments are explored from a stochastic prospective. Typical observations of the variability of soil hydraulic characteristics demonstrate the multidimensional nature of soil heterogeneity. Some recent results from three-dimensional stochastic theory are used to illustrate how large-scale mean behavior and variances can be predicted. Large-scale three-dimensional, supercomputer simulations of unsaturated flow in stochastically heterogeneous soils are used to confirm the applicability of the stochastic results. Qualitative and quantitative features of large-scale field experiments in heterogeneous soils are discussed to illustrate possible applications of stochastic theories.

HILLS, R.G.

Dept. of Mechanical Engineering,
New Mexico State University Las Cruces, USA

Model prediction and observations for infiltration into a spatially variable desert soil

The Las Cruces Trench Site experiments have been designed to provide data to test multi-dimensional field scale water flow and transport models for transport in the vadose zone. The data is of sufficient detail that both deterministic and stochastic models for spatially variable soils can be tested against observation. To test multidimensional water flow models, we use the water retention data from 450 soil core samples and 450 disturbed soil samples to formulate several different homogeneous and heterogeneous hydraulic property models for the site. The hydraulic models are used with Richards equation to predict both one- and two-dimensional infiltration at the site. Comparisons between the multidimensional experimental results and the model prediction show that the homogeneous and heterogeneous models can predict average behavior but not point behavior of infiltration into the spatially variable soil.

HUBER, M.

Ciba-Geigy AG
Basel, CH

Representing reality through models - the producer's challenge in environmental risk assessment.

KACHANOSKI, R.G., I.J. VAN WESENBEECK,, AND C. HAMLEN

Land Resource Science
University of Guelph
Guelph, CA

Spatial variability of water and solute flux in a layered soil

EXP.

The spatial variability of water and solute flux parameters were examined in a sandy loam soil, Southern Ontario, Canada. The soil is characterized by significant variability, in soil horizon thickness, with column depth varying from 0.5 m to 2.0 m. The effects of the varying horizon thickness were examined by applying a pulse of KCl to the soil surface and measuring the solute travel times at different depths using solution samplers. Measurements were taken under steady surface water flux conditions and transient rainfall conditions.

Spatial patterns of the solute travel time parameters are compared to the patterns of soil horizon properties and soil hydraulic properties.

KARLAGANIS, G.

Federal Office of Environment,
Forests and Landscape
Berne, CH

Areal solute flux estimation: legal aspects

By tradition, environmental protection in Switzerland is regulated by two laws, the water protection law of 1971 and the environmental protection law of 1983. Thus, areal solute flux has its impact mainly in the water protection regulation, were certain pollutants are regulated, such as phosphorus in slurry. However, due to areal solute flux of metal solutions, accumulation of toxic heavy metals in soils can occur. The principle of prevention in the environmental protection law has the aim to prevent such events. A close collaboration between universities, industry and administration is mandatory to take appropriate measures in time.

KLUITENBERG , G.J. AND R. HORTON

Iowa State University Ames, USA

Spatial variability of field-measured solute transport

The soil science literature contains numerous examples of measured soil physical properties which exhibit spatial correlation structure; however, few measurements have been reported which examine the spatial correlation structure of soil solute transport properties. In this paper we present the results of a field experiment designed to examine the spatial correlation structure of the solute transport properties of a glacial till soil. Chloride tracer solution was applied to plots at two locations. The tracer pulse was followed by irrigations of tracer-free water. Soil samples were collected in a square grid pattern and analyzed to yield concentration-depth profiles below each surface gridpoint. The convection-dispersion equation was fit to each concentration profile to yield estimates of D, the dispersion coefficient, and v, the pore water velocity. The parameters D and v were found to be approximately lognormally distributed as others have reported, but showed no spatial correlation over the separation distances used. The results are discussed in light of results of other correlation studies conducted near the same location.

KUTILEK, M.

Technical University
Civil Engineering Dept.
Praha, CSSR

Estimation of soil hydraulic functions from field infiltration tests

1. Evaluation of algebraic equations:
   Parameters have either approximative or no physical meaning and their distribution function is related to the type of equation used. For the evaluation of soil variability the defined fluxes are more appropriate than parameters. In majority of equations, the extrapolation of measured data is not suitable. Time variability of infiltration.
2. Infiltration is used as a defined field flux test for the solution of the inverse problem. The estimates of soil hydraulic characteristics are further applied for modeling.
3. Scaling techniques applied to infiltration with regard to areal heterogeneity and with regard to crusting and rain infiltration.

LACHASSAGNE, P. AND DE MARSILY, G.

Ecole Nationale Supérieure des mines de Paris
Centre d'Informatique Géologique
Fontainebleau, F

Two dimensional modelling of flow in saturated heterogeneous porous media: corrections of the systematic bias introduced by numerical models and application to the interpretation of pumping tests

We shall present the modifications brought to a 2-D finite differences groundwater simulation code in order to make it follow the probabilistic theory, i.e. in a "macroscopically uniform" flow, the effective transmissivity of a medium is equal to the geometric mean of the local transmissivities.

Based on this model, simulations of radial pumping tests were performed for steady and transient response in neterogeneous saturated randomly generated porous media. Consequences for the correct determination of the effective transmissivity of the aquifer will be given.

The proposed technique will be used in the analysis of field data, and in particular with those that J. Toth obtained in Olds, Alberta, Canada, in highly heterogeneous continental sediments.

LIN, C.

Dept. of Soil Science
National Chung Hsing University
Taichung, Taiwan

Characterizing the variability of the retention of solutes in a field

The temporal and spatial variability of the soil-solute interaction has been one of the major concerns on studying solute flux in soils. The reactions involve the effects of chemical constituents as well as physical properties affecting the movement of water in soils. This report, based on a case study of a field covering 16 hectare of area and 2 meters in depth, will discuss the variations of reaction parameters of heavy metals, and will propose a model to characterize the variability in the field.

LOAGUE, K. AND R.E.GREEN

Dept. of Plant & Soil Biology
University of California
Berkeley, USA

Criteria for evaluating pesticide leaching models

Mathematical models which permit query of "what it" scenarios are timely tools for assessing pesticide leaching potentials. Well-defined evaluation procedures for these obviously important models have, however, not yet been firmly established. In this paper statistical and graphical methods will be presented which, when combined, can be used to evaluate and compare alternative pesticide leaching models. An example of model testing using these methods will be discussed in detail. The pesticide leaching models to be tested in our paper will include a simple index of mobility and a deterministic-conceptual simulation algorithm. The field data that will constitute the observed data base for our model testing example will include pesticide concentration profiles estimated from deep cores taken in Hawaiian pineapple fields.

LOMEN, D.O.

Mathematics Dept.
University of Arizona
Tucson, USA

A perturbation solution for transport and diffusion of a single reactive chemical with nonlinear rate loss

LUXMOORE, R. J., G. V. WILSON, P. M. JARDINE, AND R. H. GARDNER

Oak Ridge National Lab.
Oak Ridge, USA

Use of percolation theory and Latin hypercube sampling in field-scale solute transport investigations

Scaling up from columns to pedons and from pedons to hillslopes is being aided by percolation theory and Latin hypercube sampling. Percolation theory provides a means of identifying mobile zones (backbone) and stagnant zones (backwater) for given soil structural attributes which can be compared with columns dye tracing results. The generation of frequency distributions of backwater and backbone porosities for a range of total soil porosities and pore arrangements provides stochastic data for scaling up from the columns scale to the pedon through the Latin hypercube sampling method. The scaling up from the pedon unit to the hillslope scale is based on scaling factors derived from field hydraulic characterization and the similar media assumption. The outcomes of this approach are tested against field data collected from a subsurface hydrologic facility.

MISHRA, S. AND J.C. PARKER

Virginia Polytechnic Institute
Blacksburg, USA

Effective properties for modeling unsaturated flow in large-scale heterogeneous porous media

The feasibility of representing unsaturated flow in spatially heterogeneous systems using effective parameters for an "equivalent" homogeneous medium is investigated numerically. To generate physically reasonable multivariate random fields of soil hydraulic properties, a parameter generation procedure is developed based on the assumption that local hydraulic property variations reflect differences in local particle size distribution (PSD). Local scale hydraulic properties for air-water flow are described by van Genuchten's (VG) parametric model. Saturated conductivity and VG model parameters are predicted from local particle size distribution (PSD) date using theoretically based pore structure models. Spatially variable autocorrelated fields of porosity and log-normal PSD are generated using a stochastic moving-average algorithm and then converted to distributed fields of saturated conductivity and VG model parameters. Spatial distributions and cross correlations of the multivariate parameter fields are evaluated. Two dimensional finite element simulations of steady-state unsaturated flow are conducted for several generated heterogeneous systems. Conditions under which an equivalent homogeneous porous medium with effective parameters may be used to reproduce the flow behavior of the actual heterogeneous system and the relationship between statistics of the spatially variable parameters and effective unsaturated flow properties are investigated.

MULLA, D.J. AND J.G. ANNANDALE

Dept. of Agronomy and Soils
Washington State University
Pullmann, USA

Assessment of field-scale leaching patterns for management of nitrogen fertilizer application

A 130 acre irrigated farm was intensively sampled and characterized for broad patterns in soil nitrogen fertility status and irrigation drainage. Three methods were used to assess potential patterns in solute leaching. The first two methods were changes in surface water content and temperature by time domain reflectometry and infrared thermometry, respectively, over a preplant irrigation cycle. The third method involved measuring movement of a bromide tracer applied along pairs of 600 m transects. Patterns in soil fertility and drainage were mapped using geostatistics, and analyzed using a geographic information system. These patterns can be managed with differing rates and blends of nitrogen fertilizer to minimize the potential for contamination of groundwater.

*Department of Mathmatics, University of Arizona
**Department of Soil and Water Sciences, University of Arizona, Tucson, USA

MYERS, D.E., Z. RENDUO**, AND A. WARRICK**

Geostatistical analysis of time series for the Borden field data

Known amounts of two tracers, bromide and chloride; and five halogenated organic chemicals were pulse injected into wells in an unconstrained aquifer underlying a sand quarry near Borden, Ontario, Canada beginning in August 1982 then monitored at some 5000 sites over a periode of three years. The five organics were carbon tetrachloride, bromoform, tetrachloroethylene, 1-2 dichlorobenzene and hexochloroethane. The objective was to study the spatial and temporal dispersion of the solutes. Earlier analyses used either spatial moments or time series methods to evaluate the spatial temporal behavior. To compare geostatistical methods with those of time series, three of the sites were chosen wherein all solutes were detected over a significant fraction of the three years.

Variograms (with respect to time) were modeled for each solute as well as cross variograms by pairs. HCE exhibited a random behavior with respect to time at all three sites. With one exception, the other solute variograms did not exhibit a nugget effect. Variograms were modeled by exponential or gaussian models.

After variogram fitting and autoregression time series modeling, the time series as a predictor and kriging as a predictor were compared by the use of cross-validation for CTET at one site. While the kriging errors are only slightly smaller, the relative errors for the autoregression model are significantly larger and increase with time.

NGUYEN, V.*, AND G. DAGAN**

*EWA
Minneapolis, USA

**University of Tel Aviv
Tel Aviv, Israel

Analysis of caisson transport experiments by travel time approach

The US Los Alamos National Laboratory has recently conducted extensive experiments on transport of reactive and inert solutes in unsaturated and saturated flows. The distinctive features of these caisson experiments are:

i) the scale was much larger than the usual one of laboratory columns, comparable to that of shallow soil layers, and ii) concentration and other parameters were measured under controlled conditions, which cannot generally be achieved in field. Interpreting the results by means of deterministic convection-dispersion equation was not satisfactory in matching measured concentration. In this study, we present an analysis of the experiments in a stochastic framework: the water velocity is regarded as a random space function and the transport is modeled in terms of solute particle travel time.

RAO, R.S.C., A.G. HORNSBY, R.E. JESSUP, AND K. PENNELL

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University of Florida
Gainesville, USA

Field studies on pesticide transport and transformations in the crop root zone: Experimental investigations and model evaluation

Data collected at three field sites on transport and transformations of pesticides in the citrus root zone will be presented. A number of issues pertaining to field protocols and data analyses to accommodate spatial heterogeneity (intrinsic and extrinsic) will be discussed. Comparison of several models, with differing levels of complexity, to describe these data will be reviewed.

REBER, B., C. MÄTZLER, AND E. SCHANDA

Universität Bern
Institut für angewandte Physik
Bern, CH

The use of microwave sensors in the study of water infiltration and percolation

Our group is involved in signature studies for remote sensing of the earth's surface using ground-based microwave sensors in the 1-100 GHz range. The behavior of snow and bare soil allows the determination of the surface wetness, and when compared with the rain rate, the dynamic behavior of the brightness temperatures (and backscattering coefficients) allows to draw conclusions about the areal infiltration in the surface layer.

RINALDO, A.

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University of Trento
Trento, I

A note on the formulation of solute transport in soils by lifetime distributions

The formulation of solute transport in heterogeneous media by the concentration approach and by travel time distributions is examined. The equivalence of the two formulations is recalled in the case of transport of passive solutes. The transport of reactive solutes is then examined. Solute lifetime distributions of reactive solutes in soils are viewed in the context of Taylor's theory of diffusion by continuous movements and Dagan's theory of transport through heterogeneous porous formations.

Two limit forms for the travel time approach are deduced: The first (1) is related to the case of large travel time with respect to the characteristic time of chemical-physical nonequilibrium, leading to the classic case of retardation factor in the concentration approach. It is shown that, in such a case, the travel time distribution of passive solutes with suitably "retarded" moments is the lifetime distribution. The second (2) is the limit case of short travel time with respect to the kinetics of nonequilibrium. In this case, a limit form is deduced for lifetime distributions as the product of travel time pdf's and a suitable bounded continuous function computed directly by a first-order reaction kinetics.

A discussion is then given of the perspectives of research in the general case when both relevant time scales are comparable. Concentration vs. travel time approaches are then critically reviewed in the context of application to real-life settings for solute transport in soils.

An example of application to the large scale movement of chemicals is given in the end, where limit-case (2) conditions are seemingly met.

K. ROTH

ETH Zürich

Transport of a Conservative Tracer under Field Conditions: Qualitative Modelling with Random-Walk in a Double Porous Medium

EXP.

A Chloride-tracer experiment was carried out in a heterogeneous soil under field conditions. Concentrations in the soil solution were measured in a vertical transect with 110 suction cups. The instruments were installed horizontally into the undisturbed soil from a 12m long and 3m deep tunnel. Mean vertical and horizontal spacing of the cups was 0.2 and 1.0m, respectively. Concerning transport, the most important feature of the soil were impermeable layers at the lower boundary of the measuring region.

Measured concentrations indicate that the tracer pulse splitted up into a slow and a fast moving pulse. After the infiltration of 31mm of water the fast pulse lead to an increase of Cl-concentrations in some of the deeper suction cups (at 2.6m below surface) by more than order of magnitude.

The measurements are described qualitatively be a simple model of random walk in a double porous medium with an impermeable layer at the lower boundary.

RUSSO, D., W. A. JURY , AND G. BUTTERS

ARO-Volcani Center
Bet Dagan, Israel

Numerical analysis of solute transport during intermittent leaching

Recent evidence from various field studies of solute transport suggested that downward solute velocity estimated from the concentration profiles may be significantly slower (up to a

factor of 2), or faster (up to a factor of 2) than the average downward velocity estimated from the net applied water flux and the average water content profile, whether viewed at the field scale, or viewed locally from individual field sites. In order to provide possible explanations for the differences between observed and calculated solute velocities, the influence of mobile and stagnant soil water zones on solute movement under transient nonmonotonic water flow was examined. The two-component immobile-mobile water model of solute transport was modified to describe nonreactive solute transport under transient water flow induced by periodic cycles of irrigation, redistribution and evaporation. Results of simulations of a surface-applied pulse leached by a bidaily irrigation, for different values of the mass transfer coefficient between the mobile and the stagnant water zones (α) suggested that for a given α, the apparent solute velocity (V_e) (estimated from the total volume-averaged resident concentration profiles at different elapsed times, t) decreased with t, and for a given t, V_e increased as α decreased. The total resident concentration profiles exhibited a scale-dependent dispersive behavior in the longitudinal direction, which became more pronounced as α decreased. Comparison of the results of the simulations of the transient case with those of an 'equivalent' steady-state flow model, suggested that there were significant differences in solute transport predicted by the transient two-component model compared to the steady state two-component model. These differences are caused primarily by the fact that in the transient case the portion of the water-filled pore space occupied by the stagnant region changes with time and depth (in particular near the surface). The portion of the water-filled pore space occupied by the stagnant water has a minimum during the infiltration phase which increases during the redistribution and the subsequent evaporation phases and reaches its maximum just before the successive irrigation event. Consequently, there is a considerable buildup of solute at the surface during evaporation cycles in the transient case, which is not accounted for in the steady state model.

SAGAR, B.

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Pacific Northwest Laboratory Richland, USA

Multidimensional Monte Carlo simulation of flow in variability saturated media

A Monte Carlo version of a three-dimensional liquid phase flow code has been developed to study the effects of uncertainties in the soil-moisture characteristic curves. The deterministic version of the code solves a set of coupled equations for liquid flow, heat transfer and mass transport in variably saturated geologic media which may have planar fracture. Only the soil-moisture characteristic curves are considered stochastic functions in the Monte Carlo version. Results of analysis for a layered system with stochastic independence between layer will be presented.

SCHULIN, R. AND J.C. PARKER

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Numerical analysis of the efficiency of clay liners in reducing flow through landfilled waste

A two dimensional finite element model of variably saturated flow is employed to simulate steady state water movement through vertical cross sections of a landfill subject to various design factors and assumptions regarding distributions of material properties. The waste fill, which is 30 m long in half section and 5-6 m high at the centerline, is assumed to be encapsulated by a clay liner which is horizontal at the lower surface and sloped at the upper surface to permit lateral runoff of rainfall percolating the cover soil. A steady state solution of the unsaturated flow equations is obtained subject to constant flux infiltration from net precipitation at the upper soil surface with a water table 1.0 m below the fill. Liner efficiency is characterized by the fraction of totalflow which bypasses the fill (= 1 - fraction of flow through liner). Soil properties are described by van Genuchten's model. When the clay liner is assumed to be homogeneous with a uniform saturated conductivity (K_s) of 10^{-9}

m/s, liner efficiency is predicted tc be 93%. Increasing the uniform K_s by a factor of about 2 caused liner through-flow to increase proportionately. Heterogeneous clay liners with lognormally distributed K_s having $\ln(K_s)$ variances of 0.25 and 1.0 with perfect vertical correlation of properties within the liner (over 2 rows of elements) and having the same median K_s as the homogeneous case, yielded efficiencies of only 84 and 73%, respectively. Field scale mean behavior of these cases corresponds to homogeneous liner systems with K_s values 0.5 times the arithmetic mean K_s of heterogeneous systems. This factor increases when vertical correlation of liner properties is imposed.

STAUFFER, F., AND P. JUSSEL

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Spatial variability of unsaturated flow parameters in fluvial gravel deposits

Unweathered outcrops above the groundwater table of fluvial gravel deposits near Zürich have been investigated in order to obtain information about inhomogeneities of hydraulic parameters. Different geological elements were distinguished and analysed on photographs. The spatial variability of unsaturated flow parameters was studied based on disturbed soil samples and their grain size distribution. The determination of saturated flow parameters was calibrated by undisturbed soil samples. Each geological element showed a spatial variability which strongly contrasted from other elements. The purpose of the study is a geostatistical description of the unsaturated flow parameters. The consequences of the spatial variability to mainly vertical unsaturated flow and transport processes are discussed using simple model approaches. Special emphasis is given to the role of open framework zones in the unsaturated flow and transport behaviour.

STEPHENS, D.B., AND R.S. BOWMAN

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Dept. of Geoscience Socorro, USA

Field experiment of multidimensional flow and transport in the Vadose zone

A field experiment has been in progress since January 1987. Water has been applied to an 10 m x 10 m area using a drip irrigation system. After 1 year, a pulse of bromide tracer was added. About 1 1/2 years later the flux of water was increased ten-fold and organic tracers were used to complete dispersivities. These values will be compared to column experiments in the laboratory. Detailed information on subsurface stratigraphy, moisture content distribution, pressure head, and soil temperature also will be presented.

VACHAUD, B.

Institut de Mécanique de Grenoble
Grenoble, F

Study of spatial and temporal distribution of soil moisture

Based on results obtained on different sites (Senegal, Tunisia, Spain), it suggests a method to select a priori representative sites, at a given level of probability for a selected scale of experimentation. The basic assumption is that spatial variability of soil water is not a purely stochastic process in term of space and time, but is most probably linked deterministically to soil properties such as texture.

VAN DER ZEE, S.

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Reactive solute transport in spatially variable fields

Soil heterogeneity affecting breakthrough at the ground water level may be due to spatial differences in hydraulic, chemical and recharge properties and groundwater depth. With experimental data and different models the relative contribution of these sources of heterogeneity are exposed. Sobering practical as well as theoretical results indicate some unresolved problems concerning deterministic and stochastic modeling.

WARRICK, A.

University of Arizona
Tucson, USA

Kriging versus alternative interpolators: Errors and sensitivity to model inputs

Measurements relevant to "field-scale water and solute flux in soils" are ordinarily performed to characterize physical or chemical properties or in order to predict a system response based on those properties. Because of the futility of measuring all locations for all times, applications of the results require interpolations to unknown sites and times.

Here we examine some alternative methods and compare performance. Kriging is the primary tool, but non-parametric regression and time-invariance are pursued as well. Emphasis includes not only assessments of accuracy obtained, but also a quantification of the sensitivity of the results to assumptions of the underlying random fields.

WEBSTER, R., AND T. M. ADDISCOTT

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Spatial averaging of solute and water flows in soil

Regionalized variable theory provides a comprehensive framework for describing the distributions and spatial correlation of amounts and concentrations of substances in rocks and soil. It provides the tools for estimation, decision-making and the design of sampling. Fluxes of solute and water are also random, spatially correlated and dependent on scale. They are, however, not additive, and so the theory is not so readily applicable to them. Making a reciprocal transformation of the flux gives the transfer time, a variable which is additive. The transfer time has been treated on a field scale as a probability density function. It should also be amenable to spatial averaging (kriging). The paper will consider the assumptions that underlie the treatment of the transfer time by each approach and discuss whether they are realistic in the context of practical farming. We shall also consider the applicability of regionalized variable theory to other simple models for solute and water flow. We shall discuss finally the extension of the theory from field-scale variability to that of a catchment.

WHITE, I.

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Canberra, Aus

Measurement and use of simple, physically-based parameters for predicting saturated/unsaturated infiltration flows in the field

The principal forces which govern water flow in porous materials are gravity and "capillarity". In macroscopic descriptions of saturated/unsaturated flows, the gravity contribution to flow is normally parametrized through the hydraulic conductivity K. Capillarity may be parametrized in several ways. One parametrization which has physical significance is that involving the macroscopic capillary length, l_c which is inversely related to a flow-weighted mean pore size. Equations for saturated/unsaturated infiltration can be scaled with these two parameters and this produces non-dimensional infiltration equations in which dependence on individual soil properties is second order. The approach may be extended to layered soils in which each layer is characterized by K_s and l_c. We will discuss here the in situ measurement of K_s and l_c using a variety of techniques, the spatial and temporal variability of these parameters and will illustrate their use in predicting infiltration in the field.

WHITE, R.E.

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The effect of field soil variability in water flow behaviour and indigenous solute concentrations on the use of a transfer function model to predict solute leaching

The transport of soil-derived nutrient ions, nitrate and sulphate, through defined soil volumes under the influence of surface-applied water is treated as a stochastic process. The probability density function of travel times of externally applied chloride, or the indigenous ions, was used to define the volume of soil effective in solute transport during individual leaching events, for intact cores in the laboratory or mole-and-tile drained soil in the field. The fractional transport volume Θ_{at} (m^3m^{-3}) of a soil was little affected by variable rates of water input or the initial moisture status. Thus, a soil's water flow characteristics could be reasonably well defined from the ensemble behaviour of intact cores, or the integrating effect of an underdrainage system. The major uncertainty in predicting quantities of solute leached, however, lay in estimating the initial concentration of solute in the soil's transport volume. When the value of this input variable was known accurately, good agreement between predicted and measured quantities of solute leached was obtained.

WIERENGA, P. J. AND R. G. HILLS

Soil Measurement Systems
Tucson, USA

Two-dimensional water content and solute concentration distributions during infiltration in a desert soil

There is a need for well controlled field studies to provide data to validate water flow and solute transport models for the vadose zone and to test characterization and monitoring methodologies. In this study, water containing tracers was applied over a 1 m wide by 12 m long strip at a rate of 0.5 cm/day. Water contents were measured with a neutron probe down to 6 m in three planes perpendicular to the strip and in one plane along the center of the strip. Solute concentrations were measured on a trench face perpendicular to the strip. A two-dimensional, water content based, finite difference model was used to predict infiltration at the trench site. The numerical algorithm is suitable for modeling unsaturated water flow in very dry heterogeneous systems. Comparisons between measured water contents and predicted

water contents are presented for several different homogeneous and heterogeneous hydraulic property models for the trench experiment.

WÖSTEN, J.H.M., AND S.E.A.T.M. VAN DER ZEE

The Winand Staring Center
Wageningen, NL

Use of quantified soil hydraulic variability to assess accuracy estimation of model output

Soil water retention- and hydraulic conductivity curves have been measured for a wide variety of soils in The Netherlands. The individual curves in this data base were classified in a coarse-textured, medium-textured and fine-textured soil group according to soil texture and type of soil horizon.

We use the scaling theory of similar media to quantify the existing hydraulic variability of the distinguished soil groups. Using the results of scaling model output for areas of land can now be presented in the form of a mean and variance which is attractive because it defines and reflects the uncertainty of a particular calculation.

We use the distribution function of scale factors to generate a set of 100 new soil hydraulic functions for each soil group. The success of scaling is evaluated by comparing functional criteria calculated for measured- and for newly generated hydraulic functions. In this respect functional criteria are transformations of the hydraulic functions which relate directly to practical applications (e.g. travel time of water; critical ground water depth).

JIN-ZHONG YANG

CSIRO, Centre for Environmental Mechanics
Canberra, Aus

Groundwater and soil salinity analysis in a large irrigation area

Groundwater and soil salinity balance is analysed in a large irrigated area (260 km^2). The surface irrigation water, pumping, precipitation and groundwater head data were collected for more than four years. Core samples (from soil surface to the depth of 2.5-3.0 m) were taken at fixed points to determine the salinity distribution. Based on the surface water irrigation, groundwater pumping, soil salinity and microgeomorphology, the area can be divided into seven subregions. The evaporation from and the infiltration into groundwater was analysed from data collected over four years period. A finite element model was used to calculate groundwater movement. Typical soil water profiles are given in each subregion. Soil water solute movement was considered as one-dimensional and dispersion was neglected. At each finite element nodal point a vertical water solution distribution was estimated based on the evaporation and infiltration from finite element model at that point. Comparisons of predicted salinity profile and measured profile show good agreement.

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Preface

Grimsel Test Site

Some of the most interesting, challenging and rewarding aspects of technical work associated with radioactive waste disposal result directly from the variety of tasks involved. The numerous disciplines from which contributions are required include physics, chemistry, engineering, hydrogeology and geology; the type of work ranges from theoretical and calculational studies through experimental laboratory work up to large-scale experiments or field observations. In this spectrum of tasks, increasing importance is being attached to projects involving in-situ experiments in dedicated underground facilities.

Preparations for waste disposal facilities are moving out of the pure R & D phase into a practical implementation phase. It is therefore of great value to check that lab results can be extrapolated to the field situation and also to study directly the geotechnical issues associated with engineering underground facilities, the behaviour of which must be understood and predicted over long time periods. It is also important to test at full-scale our conceptual understanding of key processes and our technical capability to carry out efficiently the tasks involved in characterising an underground repository and implementing therein the facilities for handling active wastes.

For the reasons mentioned, underground rock laboratories play a central role in the development of many disposal concepts. In most waste disposal programmes, an in-situ test facility will be an integral part of implementing a deep repository at the final chosen site. At an earlier phase in project development, underground laboratories at sites not intended for final disposal can provide valuable geotechnical knowledge of a generic nature: examples of such facilities are the Stripa mine in Sweden (which has been operated for eight years under an international cooperation agreement including Switzerland) and the Grimsel Test Site (GTS) which was excavated in 1983.

In this special issue of the «Nagra Bulletin», which is devoted to describing the GTS project, more details are given concerning the reasons which led Nagra to construct a test facility of its own and concerning the chosen emphases in the technical programme. The overall goals are to gain direct experience in underground testing and to evaluate and test experimental techniques of potential value for later characterisation of a real disposal site. Key research areas are thus the movement of groundwater and dissolved substances in fractured rock and the assessment of achievable accuracy and resolution of geophysical methods for remote sensing of rock characteristics. The developments in the first phase of the Grimsel programme have been sufficiently promising to justify extension into a second phase which has just begun and will continue until the end of 1990.

At all stages of the project one important aim has constantly been stressed. This is that the technical justification for experiments should be solidly based upon the following three basic principles: a sound concept for measurement of geotechnical parameters, a proper method for interpretation of the measured results to provide data appropriate for quantitative modelling and a demonstrated requirement for the data produced. Close collaboration is therefore needed between experimenters and modellers. This point is discussed in more depth in the introductory article which explains the choice of experimental programmes at Grimsel.

It is obvious that the technical programmes are of paramount importance in the test facility. However, the experience at Nagra has been similar to that in other countries where large-scale underground laboratories are operated: the opportunity to demonstrate technology in this way is of immense value. A hands-on demonstration is convincing not only for the lay public and politicians but also for technical experts from Switzerland and from abroad.

For Nagra staff, this fact has the positive effect of ensuring close and frequent contact with members of all the groups mentioned. Despite the shortness of the summer season which restricts free access to the facility, more than 3000 persons per year come from all over the world to visit the GTS. In addition to these numerous and varied contacts, Nagra technical staff have also had excellent opportunities for detailed exchange of information and for direct collaboration with colleagues from other countries. The most important collaboration at Grimsel has, of course, been with our German partners, but other organizations from Sweden, the USA and France have also been involved.

This Issue of the «Nagra Bulletin»

This issue is a special edition 1988 of the quarterly bulletin «Nagra informiert», which is also published in French under the title «Cédra informe». Further copies of this English special edition or free subscription to either the German or the French edition are available on request by letter from Nagra (National Cooperative for the Storage of Radioactive Waste, CH-5401 Baden, Parkstrasse 23, Switzerland, Tel. 056/205511) ■

view to carrying out joint investigations at the GTS into the properties of granite as a potential repository host rock. The work is divided up, each party bearing the costs of its proportion. The German contributions are financed by the BMFT.

The German investigations at Asse, Konrad and Gorleben are carried out by two research institutes, namely the Federal Institute for Geoscience and Natural Resources (BGR) in Hannover and the Research Centre for Environmental Sciences (GSF) in Munich. In the latter case, the research is carried out by the GSF's Institute for Deep Disposal in Braunschweig. In terms of a contract drawn up in May 1983 between Nagra on the one hand and BGR and GSF on the other, each of the German partners carries out three experiments at the Test Site. Nagra is responsible for providing the boreholes and the infrastructure and doing the construction work. The contract also provides for exchange of personnel for training purposes.

The experiments carried out by the BGR and GSF are described in more detail in the first article in this journal. In the first phase (1983–1988), the BGR was responsible for the electromagnetic high-frequency measurements, the fracture system flow test and rock stress measurements, while the GSF participated with the tilt measurements, the heating test and the ventilation test. The German-Swiss cooperation in the GTS project has proved positive for all parties involved. It was therefore decided when planning Phase 2 (1988–1990) that the arrangement should continue until the end of 1990. Each partner will continue a major test project – the BGR the fracture system flow test, the GSF the ventilation test and Nagra the migration experiment. In addition, Nagra will begin two new research projects.

United States of America

A cooperation agreement has existed between the Departement of Energy in Washington (DOE) and Nagra since 1985. This foresees the exchange of both information and research results and provides the framework for cooperation in the field of in situ investigations. Nagra also signed a similar contract in 1986 with the safety authority in the USA, namely the Nuclear Regulatory Commission (NRC). The initial founding agreement with the DOE has been consolidated with a further three-year agreement; this was drawn up in 1987 with reference to specific investigations. Specific programme suggestions are also presently under review with the NRC.

The project-specific contract with the DOE assumes that both Nagra and the DOE have a direct interest in improving repository safety analysis methods, that the DOE already has wide theoretical experience in this area and that a considerable amount of in situ data will be acquired from boreholes and from the GTS in the course of the Nagra programme.

Experts of both partners with experience in theoretical investigations will now be able to work in close cooperation with the experimenters who produce Nagra's in situ data. The whole process will run something like the interaction between modelling and in situ investigations described in the first article in this journal.

Sweden

The Swedish and Swiss concepts for high-level waste (HLW) disposal are similar in many respects. For example, they have in common a granite host rock, a network of underground disposal tunnels and the use of bentonite as a backfill- and buffer-material and for the sealing of boreholes. With regard to timescales, the SKB plan to have a HLW repository operational by the year 2020 corresponds basically to that of Nagra. Since Sweden began its research into waste disposal at a very early stage and has since carried out very important and relevant work, the Swedish programme is recognised world-wide as leading in the field.

In October 1980, a contract was drawn up between Nagra and its Swedish sister SKB, in terms of which Nagra works closely with Swedish experts and technicians; Nagra has also participated in the Stripa project since 1980. This close contact occurs at all levels – from advice in planning scientific research programmes to detailed questions relating to measuring equipment.

For certain in situ investigations, for example the large-scale tests on bentonite backfilling and sealing, Nagra relies to a large extent on Swedish experiments (Stripa) and carries out what is essentially complementary work in Switzerland. The allocation of contracts from the Nagra programme to Swedish institutions or contractors who have already participated in the SKB programme also promotes a close working relationship between the two countries. Good examples of this are the repeated use of a team from the Swedish Geological Service (SGAB) with highly developed equipment for the radar measurements at the Grimsel Test Site (see the article on tomographic investigations in this journal) and the planned GTS «prediction ahead of tunnel face» project which will also involve the SGAB to a large extent.

Further cooperation with experts from other countries

The development and performance of Nagra field investigations and the GTS experimental programme have also profited from innumerable further examples of cooperation on a smaller scale. Individual experts, mainly from Great Britain, the USA and Canada, have acted as advisers in project planning. Contractors from many countries were involved in Nagra's regional geology programme which included several deep boreholes and a wide range of reconnaissance work. German drilling experts, Canadian hydrogeology service companies and French seismic investigation teams are just a few examples. French researchers were also responsible for reviewing geophysical measuring techniques as part of the Grimsel programme.