CENTER FOR NUCLEAR WASTE REGULATORY ANALYSES

TRIP REPORT

SUBJECT: Fifth Canadian-American Conference on Hydrogeology: "Parameter Identification and Estimation for Aquifer and Reservoir Characterization" (20-3702-072)

DATE/PLACE OF TRIP: September 18-20, 1990
The Westin Hotel
Calgary, Alberta, Canada

AUTHOR: Rachid Ababou

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SUBJECT: Fifth Canadian-American Conference on Hydrogeology: "Parameter Identification and Estimation for Aquifer and Reservoir Characterization"

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The Westin Hotel
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AUTHOR: Rachid Ababou

PERSON PRESENT:

CNWRA

Rachid Ababou

BACKGROUND AND PURPOSE OF TRIP:

This is the fifth of a continuing series of Canadian-American conferences on Hydrogeology, sponsored by the Association of Groundwater Scientists and Engineers, which publishes the Groundwater Journal. This particular conference on "Parameter Identification and Estimation for Aquifer and Reservoir Characterization" was co-sponsored by the Alberta Research Council. There were about 40 speakers at the three-day conference, with topics ranging from geological process simulation to geostatistical and stochastic approaches for hydrogeological characterization. Mainly two types of applications surfaced: (1) hydraulic and advective-dispersive properties of contaminated aquifers, and (2) oil and gas reservoir characterization. We heard about laboratory scale studies (thin slices), geological measurement methods, aquifer scale tracer experiments, and large-scale studies on regional and interconnected groundwater flow systems. I presented a paper on the "Identification of Effective Conductivity Tensor in Randomly Heterogeneous and Stratified Aquifers." This work focused on the effective, macroscale flow properties of naturally heterogeneous geologic formations, particularly those with preferentially oriented structures and/or composites made up of distinct units. The conference program, list of participants, and pre-proceedings abstracts are enclosed. A brief overview of the meeting is given below.

SUMMARY ANALYSIS OF SELECTED PRESENTATIONS:

Stochastic Approaches and Effective Parameters

Here are some highlights on the stochastic approach. Opening the first day session, *Lynn Gelhar* (Massachusetts Institute of Technology) provided an extensive review of the stochastic approach to subsurface flow and transport, illustrated by analyses of field tracer tests, such as the Columbus air force base site and others. Assembling data from a number of contamination events and tests around the world, he indicated on a log-log plot the roughly linear

increase of contaminant plume dispersity, from centimeters to tens of kilometers, with increasing scale of contamination from meters to hundreds and thousands of kilometers (e.g. state of Iowa).

Alexander Desbarats (Geological Survey of Canada) presented a technique to extend previous stochastic results on effective conductivity of randomly heterogeneous formations to the case of finite domains (finite scale of support); he successfully backed up his proposal with numerical experiments for the 2-dimensional, assuming isotropic and gaussian log-conductivity distribution.

Rachid Ababou (i.e. myself), Center for Nuclear Waste Regulatory Analyses, presented a tensorial power-average expression that relates the anisotropic effective conductivity to simple statistical parameters such as mean, variance, and directional fluctuation scales of the geologic formation. The result is applicable, in principle, to the important case of non-symmetric and bi-modal log-conductivity distributions. The proposed relation was backed up using a number of available results (exact, asymptotic, and numerical). The tensorial relation was then used as a parameter estimation method with data from the Oracle fractured granite site where fractures appear to be the dominant cause of anisotropy.

Stefan Bachu, conference organizer, and his colleagues, D. L. Cuthiell, J. W. Kramers, L. P. Yuan, all from the Alberta Geological Survey, presented an extensive geologic and hydraulic study of an oil sand reservoir near Provost, Alberta. They used an impressive battery of geophysical and laboratory techniques to describe the relatively homogeneous sand facies as well as the very heterogeneous shale clast facies (shale breccia in a sand matrix). The latter facies was precisely described using digitized thin sections from undisturbed core sample. The data were used for numerical flow experiments aimed at retrieving the effective conductivity in such a sharply bi-modal type of heterogeneous medium.

Brian Berkowitz (Water Commission, Israel) presented a focused study of the percolation problem through conducting discs (in 2D) and conducting spheres (in 3D), and recovered some known results in the process. He looked in particular at what happens with "overlapping" spheres, assuming that bond conductivity is a power function of the overlap.

Leslie Smith (Univ. of British Columbia) compared statistical continuum and discrete network predictions of flow and solute transport in fractured media. He started with the case of an orthogonal network with randomly distributed fracture lengths. Statistical continuum flow was then constructed by using statistical features of the velocity field as observed ("measured") on the discrete network simulation. It was shown that the leading edge and tail of a concentration plume could be simulated well with the continuum approach, provided however that certain details of the velocity distribution be faithfully reproduced (gamma rather than log-normal, and second-order autoregressive rather than uncorrelated). He proposed a hybrid dual-permeability method to simulate transport in more complex, hierarchical media, e.g. two-scale fracture networks (the breakthrough curves are bi-modal, i.e. double-humped). Briefly, his method models the dominant fractures explicitly, but subsumes the denser, sub-dominant fractures (and porous matrix?) as separately modeled blocks. These blocks are sub-domains bordered by the major fractures. The advantage of this approach is that it breaks up the large flow-transport problem into smaller problems. One drawback is that the effective transport processes specific to each sub-domain must still be generated These sub-domain processes are expressed in terms of transition probabilities on travel time and exit location, and are not universal because of the sub-REV size of the individual blocks

Best Linear Estimators and Geostatistical Approaches:

Peter Kitanidis (Stanford University) presented a Bayesian, "best linear estimator" approach to the inverse problem. He started with examples illustrating the non-uniqueness of the inverse problem for groundwater flow: the conductivities obtained by direct solution of the inverse problem vary wildly in space and are non-unique (1D example). Thus, instead of computing many possible solutions, he proposes to assign probabilities and compute a "weighted mean" from all possible inverse solutions. His approach to compute this "weighted mean" of all possible inverse solutions is: (1) maximize the entropy of the p.d.f., a measure of solution multiplicity, subject to physical constraints (cross-correlations between parameters and flow field, known theoretically from linearized flow equation) and subject to other reasonable constraints (assumed spatial covariance structure of the parameters), and (2) account for measurements through Bayes theorem on conditional probabilities (same as in kriging). The result gives an estimate of the p.d.f. of all possible solutions to the inverse problem. Cross-validation tests are essential to confirm the results. An example was given in the case where the true, unknown aquifer is composed of two conductivity blocks (a highly non-gaussian situation).

Eileen Potter (Colorado School of Mines) used conditional simulation with indicator variables to describe the interconnected lithofacies at the Hanford site. An indicator variable takes only two or a few values, e.g. code numbers pointing to the type of facies or some other geologic descriptor. In this particular case, Monte-Carlo indicator conditional simulations were used to explore the probability of having a continuous path through the most permeable facies (sand and gravel).

Geology versus Hydrology:

A number of presentations were made on quantitative interpretation of geological patterns. *Mary Anderson* (Univ. of Wisconsin-Madison) presented a general exposé on the problem of transfering geological information to hydrological models She focused in particular on the case of sedimentary formations, e.g., proximal to distal facies distribution in an alluvial fan. She advocated the use of Miall's "architectural elements" analysis, emphasized the importance of interconnections between widely different geologic units, and proposed using models of geological processes to simulate (reproduce) generic facies. Her student, Erik Webb, presented the results of such a "facies model" using Stanford University SEDSIM code (Tetzlaff and Harbaugh, 1989). The scale of simulated geology is tens of kilometers. There are obvious limitations due to lack of space-time resolution and due to simplified or unmodeled phenomena (cross-bedding patterns are not generated). Finally, Mary Anderson pointed out several specific instances of described geologic variability, e.g. vertical variability within the core of an esker (Shaw, 1972); a case of a bi-modal aquifer (indicator kriging mapping by Johnston and Rice); outcrop maps from the meter to tens of meters scale (Frazer & Cobb, 1982); and a simulated case of funneled flow and transport.

The presentation by *John Kramers* et al. (Alberta Research Council) was a case study of the sandy facies of the Provost sand oil reservoir in Alberta (the shale clast layers were studied by colleague *Stefan Bachu*, as discussed above with "stochastic approaches"). Geophysical tools were used extensively. In addition, thin section analyses from the 11.6 cm diameter core were used to relate porosity and "pore connectivity" to permeability based on linear regression. Pore "connectedness" was classified (end members 1,2,3,4). The conclusion was that,

in spite of a large-scale vertical trend the fend facies was relatively homogeneous except for the interspersed . 'a clast layers.

David Thomson, from the Alberta Research Council, and John Cherry, attempted to recover a mean "fracture spacing" for their deep clayey till by comparing the "large-scale" hydraulic conductivity of single-well pumping test with small core conductivity data. The small scale laboratory conductivities were about 2 orders of magnitude smaller than the pumping test result. They used a simple analytical solution with simple fracture network model to recover the "fracture spacing" (1-5m)

Elizabeth Jacobson, Desert Research Institute, presented an updated statistical analysis of the Las Cruces trench soil data. The Las Cruces trench is the site of one of the dozen or so INTRAVAL test cases, and is being used by NRC and CNWRA for unsaturated flow-transport model validation. The saturated conductivity data were analyzed directionally (vertical, horizontal), by layers, and by combining statistically similar layers (certain soil horizons from different depths were therefore re-grouped). The results were expressed in terms of variograms, variances, correlation scales, etc

John Wilson (with Fred Philips), New Mexico Institute of Mining and Technology, discussed the role of geology in parameter estimation through a field study of an outcrop in Rio Grande fluvial deposits interspersed with paleo-soils. They used the alluvial "architectural elements" classification of Miall (1985), and further assumed the conductivities to be strongly related to such alluvial classification, i.e. controlled by the depositional process that generated the alluvium. This assumption was used to construct the conductivity map of the outcrop face, along with direct conductivity measurements using hand-operated air-permeameter.

Lisa Shepherd, Univ. of Wisconsin-Madison, presented thin slice analyses from the Saint-Peter sandstone's overpressured zones (Michigan basin). Focusing on the two-dimensional (cross-sectional) porosity, she found very high microscale variability (0.1 to 0.20 porosity) compared to the remarkable macroscale homogeneity of this sandstone. She concluded that there may be dominant effects of secondary diagenetic processes (secondary cementation) and is now looking at banded cementation features. It should be noted that small averaging windows were used to infer porosity heterogeneity; the dependence of perceived heterogeneity with scale of averaging was not analyzed.

Rainer Senger from the Bureau of Economic Geology, Austin, presented a basin-scale analysis of variable density flow through a cross-section of the Palo Duro basin, and tested several paleohydrogeologic scenarios.

Larry Lake, Univ. of Texas at Austin (Petroleum Engineering), tested two approaches to miscible displacement in a heterogeneous eolian formation, the Page Sandstone in northern Arizona Using field data from the Page Sandstone outcrop, a detailed "truth case" was simulated using 11,000 nodes with actual aquifer properties at each node. The "truth case" was then compared to: (1) a "pseudo-function" simulation, where effective properties are used to model flow behavior in relatively coarse-scale flow units, and (2) a conditional simulation approach where interwell properties are generated statistically. In both cases, only "geological information" and a few well data are assumed to be known (less than were used to generate the "truth case")

IMPRESSIONS/CONCLUSIONS:

This conference in my view was quite successful, being just the right combination of applied and theoretical studies In addition, several presentations appeared to offer complementary concepts, methods, and sometimes solutions to the hydrodynamic parameter estimation from observations that are incomplete, localized, sparse, qualitative, or only indirectly related to hydrodynamics. My own paper on "Identification of Effective Conductivity Tensor in Randomly Heterogeneous and Stratified Aquifers" was one of a few which focused on generic approaches to reconstitute effective conductivities from statistical hydrogeologic information. I contacted, and was contacted by, a number of persons at the workshop for exchange of information and data; these exchanges were constructive and fruitful

PROBLEMS ENCOUNTERED:

None

PENDING ACTIONS:

None

RECOMMENDATIONS:

Attendance at such meetings plays in 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 — October 1, 1990.

Rachid Ababou — Date

CONCURRENCE SIGNATURES

John L Russell — October 1, 1990

John L Russell — Date

Allen R Whiting — October 2, 1990

Allen R Whiting — Date

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Attachments

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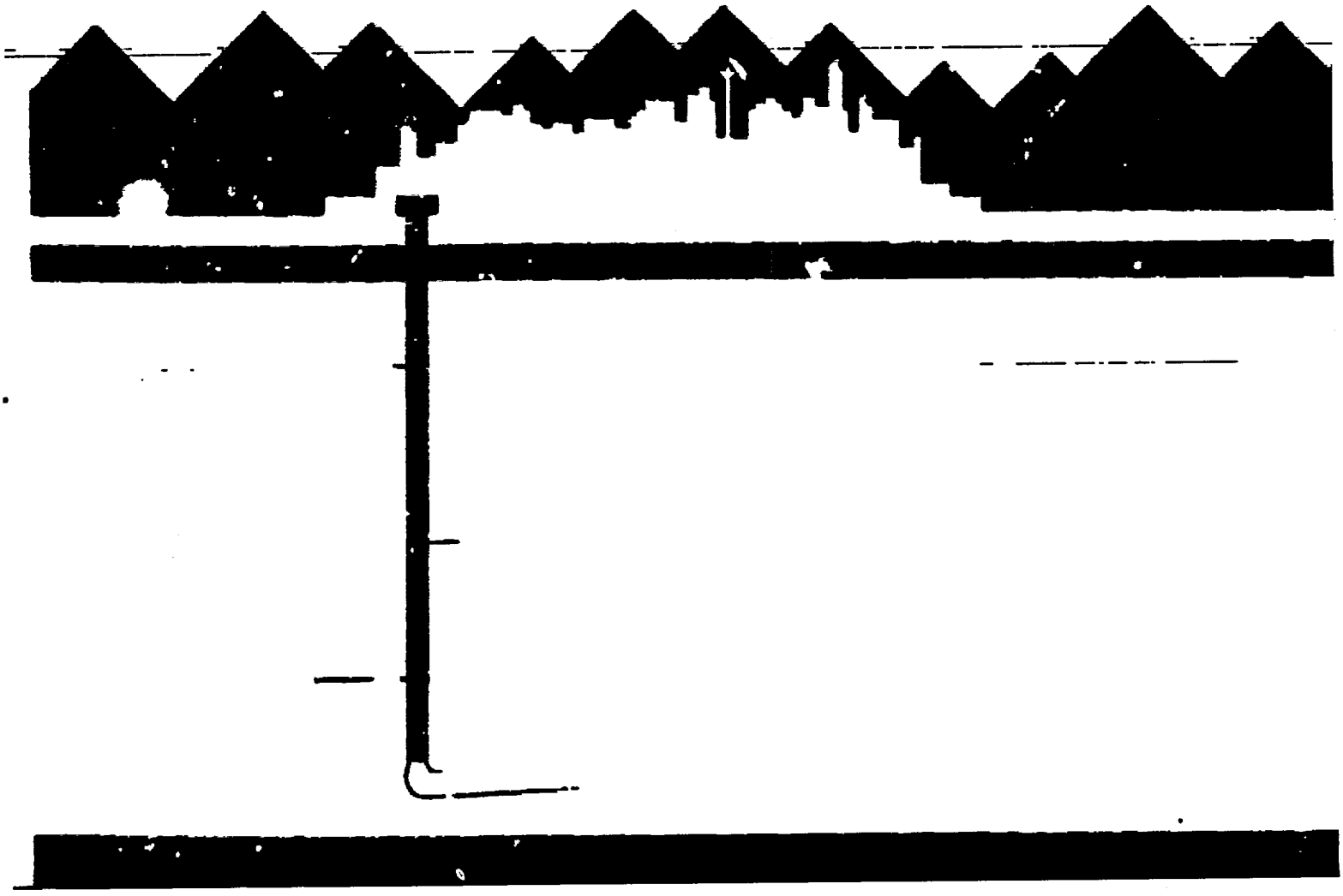
The Fifth Annual Canadian/American Conference on Hydrogeology

Parameter Identification and Estimation for Aquifer and Reservoir Characterization

September 18-20, 1990
The Westin Hotel
Calgary, Alberta, Canada



PROGRAM AND SCHEDULE

Monday, September 17, 1990

18:00 - 20:00	Registration at Westin Hotel, West Foyer
19:00 - 21:00	Wine and cheese get-together, Bonavista Room, Westin Hotel

Tuesday, September 18, 1990

07:00 - 08:15	Continental Breakfast - Mayfair Room
	Presentations - Mayfair Room
08:30 - 08:35	Opening remarks (Stefan Bachu)
	Session Chairman - Mary P. Anderson
08:35 - 09:40	Lynn Gelhar, Massachusets Institute of Technology, Cambridge, Massachusetts: *Stochastic characterization of subsurface flows*
09:40 - 10:00	Alexandr. J. [illegible], Geological Survey of Canada, Ottawa, Ontario: *Spatial averaging of transmissivity*
10:00 - 10:20	Coffee Break
10:20 - 10:40	Jeff Riddle, Salt River Project, Phoenix, Arizona: *Kriging application to estimate ground water and top of aquifer elevations for eastern Arizona*
10:40 - 11:00	Rachid Ababou, Southwest Research Institute, San Antonio, Texas: *Identification of effective conductivity tensor in randomly heterogeneous and stratified aquifers*
11:00 - 11:20	Joost Herweijer[1] and Steven C. Young[2], [1]GeoTrans Inc., Herndon, Virginia and [2]Tennessee Valley Authority, Norris, Tennessee: *Use of detailed sedimentological information for the assessment of well tests and tracer tests in a shallow fluvial aquifer*
11:20 - 11:40	Steven C. Young[1], Joost C. Herweijer[2] and Dudley J. Benton[1], Engineering Laboratory, Tennessee Valley Authority, Norris, Tennessee [2]and GeoTrans Inc., Herndon, Virginia: *Geostatistical evaluation of a three dimensional hydraulic conductivity field in an alluvial terrace aquifer*
11:40 - 12:00	Saleem G. Ghori and John P. Heller, New Mexico Institute of Mining and Technology, Socorro, New Mexico: *Determination of permeability heterogeneity from a field tracer test through an improved numerical method*
12:00 - 13:15	Lunch - Belaire Room

Tuesday, September 18, 1990

Session Chairman - Lynn Gelhar

13:15 - 14:00 Mary P. Anderson, Department of Geology & Geophysics, University of Wisconsin - Madison, Madison, Wisconsin.
Aquifer heterogeneity -- a geological perspective

14:00 - 14:20 Erik K. Webb and M.P. Anderson, Department of Geology and Geophysics, University of Wisconsin - Madison, Madison, Wisconsin:
Using a sedimentary depositional model to simulate heterogeneity in glaciofluvial sediments

14:20 - 14:40 John W. Kramers, Li Ping Yuan, Stefan Bachu and David Cuthiell, Alberta Geological Survey, Alberta Research Council, Edmonton, Alberta:
Reservoir characterization case study: sandy facies

14:40 - 15:00 Stefan Bachu, David Cuthiell, John Kramers and Li Ping Yuan, Alberta Geological Survey Alberta Research Council, Edmonton, Alberta:
Reservoir characterization case study: bimodally heterogeneous facies

15:00 - 15:20 Coffee Break

15:20 - 15:40 Richard J. Stebnisky[1] and H. Leonard Vacher[2], [1]J.B. Butler and Associates, Inc., Tampa, Florida and [2]University of South Florida, Tampa, Florida:
Hydraulic conductivity predicted as a function of grain size, sorting and porosity for dune, washover and foreshore depositional environments on a barrier island in Florida, USA

15:40 - 16:00 Fred G. Baker and H.F. Pavlik, Woodward-Clyde Consultants, Denver, Colorado and EBASCO Environmental, Lakewood Colorado:
Characterization and modelling of ground water flow in a heterogeneous aquifer system to evaluate contaminant migration

16:00 - 16:20 David G. Thomson[1] and John A. Cherry[2], [1]Environmental Research and Engineering Department, Alberta Research Council, Edmonton, Alberta and [2]Institute for Groundwater Research, University of Waterloo, Waterloo, Ontario:
Hydraulic evidence of Wisconsinan-aged open fractures in a deep clayey till

16:20 - 16:40 Baoren Chen[1] and Peikang Jin[2], [1]Earth Sciences Department, Nanjing University, Nanjing, China and [2]The Nanjing Institute of Hydrology, Nanjing, China:
The spectrum features of deep water-bearing system and research of transfer function

Wednesday, September 19, 1990

07.00 - 08.15 Continental Breakfast - Mayfair Room

Lectures - Mayfair Room

Session Chairman - John L. Wilson

08.30 - 09.40 Leslie Smith, Tom Clemo and Mark Robertson, Department of Geological Sciences, University of British Columbia, Vancouver, British Columbia:
New approaches to the simulation of field-scale solute transport in fractured rock masses

09.40 - 10.00 Peter S. Baker and W.A. Murray, ABB Environmental Services, Inc., Portland, Maine:
Use of pumping test data to determine radial and non-radial flow zones in a fractured limestone aquifer

10:00 - 10:20 Coffee Break

10:20 - 10:40 Brian Berkowitz[1] and I. Balberg[2], [1]Water Commission, Ministry of Agriculture, Jerusalem, Israel and [2]The Racah Institute of Physics, The Hebrew University of Jerusalem, Jerusalem, Israel:
A percolation model for hyraulic conductivity in porous media

10:40 - 11:00 Eileen Poeter and Peter Townsend, Colorado School of Mines, Golden, Colorado:
Delineating aquifer heterogeneity with stochastic multiple indicator conditional simulation of the unconfined aquifer, Hanford Site, Washington, USA

11.00 - 11.20 Elizabeth Jenkins, Desert Research Institute, University of Nevada, Reno, Nevada:
Investigation of the spatial correlation of saturated hydraulic conductivities from a vertical wall of a trench

11:20 - 11:40 Kevin K. Wolka[1] and T. Al Austin[2], [1]Geraghy and Miller, Inc., Troy, Michigan and [2]Department of Civil and Construction Engineering, Iowa State University, Ames Iowa:
Stochastic modelling of contaminant movement in ground water

11.40 - 12.00 Geoffrey C. Bohling[1], Jan Hartl[2] and John C. Davis[1], [1]Kansas Geological Survey, University of Kansas, Lawrence, Kansas and [2]Central Institute for Physics of the Earth, German Democratic Republic:
Regionalized classification: ideas and applications

12 00 - 13:15 Lunch - Belaire Room

Wednesday, September 19, 1990

Session Chairman - Leslie Smith

13:15 - 14:00 John L. Wilson and Fred M. Phillips, New Mexico Institute of Mining and Technology, Socorro, New Mexico:
The role of geology in parameter estimation

14:00 - 14:20 Timothy D. Scheibe and David L. Freyberg, Department of Civil Engineering, Stanford University, Stanford, California:
Understanding the impacts of spatial structuring of natural porous media on the modelling of solute transport in groundwater

14:20 - 14:40 Lisa D. Shepherd, Jean M. Bahr and Gerilynn R. Moline, Department of Geology & Geophysics, University of Wisconsin - Madison, Madison, Wisconsin:
Determination of scales of porosity variability through the use of image analysis

14:40 - 15:00 Gerilynn R. Moline, J.M. Bahr and L.D. Shepherd, Department of Geology & Geophysics, University of Wisconsin - Madison, Madison, Wisconsin:
A multivariate statistical analysis of wireline log data for the determination of hydrostratigraphy and hydraulic parameters: St. Peter sandstone, Michigan Basin

15:00 - 15:20 Coffee Break

15:20 - 15:40 John L. Wilson, New Mexico Institute of Mining and Technology, Socorro, New Mexico:
Visualization of flow and transport in heterogeneous media

15:40 - 16:00 Iraj Ershaghi[1], H. Calisgan[1] and Y. Shikari[2], [1]Department of Petroleum Engineering, University of Southern California, Los Angeles, California and [2]Gas Research Institute, Chicago, Illinois:
Estimation of reservoir parameters in heterogeneous gas storage reservoirs under aquifer support

16:00 - 16:20 Salt Kocberber and R. Eugene Collins, Research and Engineering Consultants, Inc., Texas:
The impact of large scale heterogeneities on hydrocarbon recoveries

16:20 - 16:40 V.A. Mironenko, Mining Institute, Leningrad, USSR:
Assessment of the rational set of field tests in heterogeneous aquifers using simulation models

Thursday, September 20, 1990

07 00 - 08:15 Continental Breakfast - Mayfair Room

Lectures - Mayfair Room

Session Chairman - Larry Lake

08.30 - 09:40 Peter K. [illegible] Water Resources, Department of Civil Engineering, Stanford University, Stanford, California:
A conceptual framework for the geostatistical approach to the inverse problem

09 40 - 10:00 Bryan J. Travis, Earth and Environmental Sciences Division, Los Alamos National Laboratory, Los Alamos, New Mexico:
Recovery of discontinuities using a parametric form of regularized inversion

10.00 - 10:20 Coffee Break

10:20 - 10:40 Jiannan Xiang and Derek Elsworth, Department of Mineral Engineering, Pennsylvania State University, University Park, Pennsylvania:
A comparison of several optimization methods for inverse solution of ground water flow systems

10.40 - 11:00 Robert Ritzi, Department of Geological Sciences, Wright State University, Dayton, Ohio:
Inverse modelling in the frequency domain: the example of estimating hydraulic conductivity from observations of the combined solid earth tide and atmospheric pressure influence

11.00 - 11:20 P.R. McGillivray and D.W. Oldenburg, Department of Geophysics & Astronomy, University of British Columbia, Vancouver, British Columbia:
The inversion of pole-pole resistivity data in the solution of ground water contamination and enhanced oil recovery problems

11:20 - 11:40 Malcolm Reeves and Rebecca Yost Grambo, Geological Engineering Department, University of Saskatchewan, Saskatoon, Saskatchewan:
Modelling a multi-unit aquifer system with uncertainty in both aquifer properties and aquifer geometry

11:40 - 12.00 James C. Redwine[1], Richard R. Parizek[2] and Fred J. Molz[3], [1]Southern Company Services Inc., Birmingham, Alabama, [2]Pennsylvania State University, University Park, Pennsylvania and [3]Department of Civil Engineering, Auburn University, Alabama:
Controls on porosity and permeability in fracture-flow/conduit-flow rocks of the Knox Group, Southern Appalachian fold-and-thrust belt, USA

12:00 - 13:15 Lunch - Brittania Room

Thursday, September 20, 1990

Session Chairman - Peter K. Kitanidis

13:15 - 14:00 • Larry Lake, Department of Petroleum Engineering, The University of Texas at Austin, Austin, Texas:
Simulating fluid flow through a geologically realistic permeable medium

14:00 - 14:20 E.N. Yearsley and R.E. Crowder, COLOG, Inc., Borehole Geophysical Services, Golden, Colorado:
Review of state-of-the-art borehole geophysics applied to hydrogeology

14:20 - 14:40 Bruce Manchon, International Technology Corporation, Martinez, California:
Aquifer parameters defined by borehole geophysics

14:40 - 15:00 Rainer Senger, Bureau of Economic Geology, The University of Texas at Austin, Austin, Texas:
Regional characterization of variable-density fluid flow in sedimentary basins: implications on modelling strategy

15:05 - 15:20 Coffee Break

15:20 - 15:40 Emanuel Mazor and Adi Bosch, Geoisotope Group, Weizmann Institute of Science, Rehovot, Israel:
Boundary conditions for modelling of ground water and petroleum systems: noble gas contributions

15:40 - 16:00 Emanuel Mazor[1] and Levy Kroitoru[2], [1]Geoisotope Group, Weizmann Institute of Science, Rehovot, Israel and [2]Battelle, Willowbrook, Illinois:
Boundary conditions needed for ground water modelling, derived from isotopic, chemical and physical measurements: Mediterranean-Dead Sea transect

16:00 - 16:20 Joe O. Davis, Omega Geophysics Ltd., Burrard Street, Vancouver, British Columbia:
Remote sensing of contamination using geophysical electromagnetic methods

16:20 - 16:40 P.N. [illegible], Department of Applied Geology, University of Madras, Madras, India:
Geoelectrical parameters in hard rock hydrogeology

16:40 - 16:45 Closing Remarks

• - Invited Speaker

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about the author...

Lynn W. Gelhar is Professor of Civil Engineering at Massachusetts Institute of Technology where he teaches ground water hydrology He is recognized as a leading authority in the new field of stochastic subsurface hydrology, having received the American Geophysical Union's Horton Award and the O E Meinzer Award by the Geological Society of America in recognition of his pioneering work in this area. Dr. Gelhar is currently preparing a textbook entitled Stochastic Subsurface Hydrology" to be published by Prentice-Hall, Inc. He has extensive consulting experience with government and industry on problems of hazardous and radioactive waste disposal

Mailing address.

Massachusetts Institute of Technology
Room 48-329
Cambridge, Massachusetts
02139, USA

Stochastic characterization of subsurface flows

Lynn W. Gelhar

The last decade has seen major developments of stochastic theories which have revolutionized the way in which we conceptualize and characterize subsurface flow and transport processes in naturally heterogeneous media. Experience with large scale numerical simulations and intensively sampled field research sites has confirmed the validity of stochastic theoretical approaches, but the application of the theoretical results to actual field problems has been very limited, largely because of the difficulty of determining the stochastic parameters which characterize spatial variability in natural subsurface material. The focus of this paper is this challenging stochastic characterization problem First some key theoretical results are reviewed to emphasize the basic concepts and the role of the important stochastic parameters. Some measurement techniques which have proven to be useful to characterize spatial variability of hydraulic conductivity are described briefly, emphasizing, in particular, tools which have potential for routine use in field applications. The results of stochastic characterization at several field research sites indicate that definitive spatial correlation structures can be identified at each individual site. On the other hand, results from a large number of investigations of field heterogeneity, when summarized graphically, appear to indicate a scale dependence of spatial correlation scales. The prospects for improved characterization of heterogeneous subsurface flow systems are discussed with emphasis on the role of large-scale heterogeneity and the use of indirect geological information.

about the author...

Alexander Desbarats is a research scientist with the Mathematical Applications in Geology Section of the Geological Survey of Canada in Ottawa. He obtained a BA in geological engineering and an MA in applied science (geostatistics) from the Ecole Polytechnique of Montreal in 1980 and 1982 respectively. In 1987 he obtained his PhD from the Department of Applied Sciences of Stanford University. His thesis research dealt with the stochastic modelling of fluid flow in sand-shale sequences. Since July 1987 he has been with the Geological Survey of Canada where he conducts research on fluid flow and solute transport in heterogeneous formations.

Mailing address:

Geological Survey of Canada
601 Booth Street
Ottawa, Ontario
K1A 0E8

Spatial averaging of transmissivity

Alexander J. Desbarats

Several previous authors have shown that the effective transmissivity of an infinite, statistically isotropic formation is given by the ensemble geometric mean of the random transmissivity field when transmissivities are log-normally distributed. In this paper, an earlier analytical approach of Matheron is modified to show that the effective transmissivity of a finite region such as represented by a simulator grid block is obtained by spatial geometric averaging of point support-scale transmissivities within. The ensemble properties of the block support-scale spatial random function thus defined are shown to depend on the area of spatial averaging and on transmissivity covariance structure. For a second-order stationary and ergodic transmissivity field, the expected block average transmissivity decreases towards the ensemble geometric mean as the averaging area becomes large compared to the correlation range.

The validity of spatial geometric averaging is evaluated using a numerical model of steady-state ground water flow in a simulated heterogeneous transmissivity field discretized on a point support-scale grid. The transmissivity field is generated by an analog method based on digital terrain elevations from the Walker Lake area of Nevada. Log-transmissivities exhibit a bimodal distribution with a variance near 1.0 and an anisotropic covariance structure. Despite these departures from assumed conditions, predicted block-averaged transmissivities are found to be in excellent agreement with true values obtained from the flow simulation. The support-scale dependence of block averaged transmissivities is clearly observed and is well described by theoretical results. Limitations to the applicability of spatial geometric averaging are discussed in light of these results.

about the author...

Jeff Riddle earned his BS in geology in 1981 from Midwestern State University, Wichita Falls, his MS in hydrology in 1984 from the University of Arizona, Tucson. He has five years experience at the Geohydrologic Project, including regional flow modelling, water well drilling and land subsidence investigations.

Mailing address:

Jeff Riddle
Salt River Project
PO Box 52025
Phoenix, Arizona
85072-2025, USA

Kriging application to estimate ground water and top of aquifer elevations for eastern Arizona

Jeff Riddle

The Salt River Project (SRP) monitors the water resources of the St. Johns, Arizona area due to requirements contained in the siting agreement for its electrical generation plant. In an effort to enhance the monitoring, the SRP implemented a ground water model which requires, among other things, the regional characterizations of ground water elevations (GWE) and top of aquifer elevations (TAE). Kriging and its associated forms of output have recently been applied to enhance these characterizations.

As part of the kriging process, variogram plots were reviewed and models were chosen with the following constraints.

	GWE	TAE
Model types	Gaussian	Nuggett & Gaussian
Major axis length (mi)	20	9
Minor axis length (mi)	20	9
Major axis orientation	15R north of east	15R north of east

The kriging seems to have produced a good overall interpolation of elevations. Specifically, cross validations show less than 15% of the SWE interpolations were more than 100 ft different than field values and less than 15% of the TAE interpolations were more than 200 ft different than the field values. Additionally, several of the worst cross validations for TAE were in the vicinity of structurally deformed areas.

about the author...

Rachid Ababou is currently conducting research on theoretical and computational approacnes for modelling stochastic flow and transport phenomena in highly heterogeneous, three-dimensional conductive media. He received his Dr Ing (honours) in fluid mechanics from the University of Grenoble in 1981 and his PhD in civil engineering from MIT, Cambridge. Dr. Ababou has published a book chapter and several papers in refereed literature. He is currently a senior research scientist with the Center for Nuclear Waste Regulatory Analyses, San Antonio, Texas.

Mailing address:

Southwest Research Institute, Division 20
Center for Nuclear Waste Regulatory Analyses
6220 Culebra Road
San Antonio, Texas
78228-0510, USA

Identification of effective conductivity tensor in randomly heterogeneous and stratified aquifers

Rachid Ababou

Identification of a macro-scale "effective" hydraulic conductivity tensor in heterogeneous and imperfectly stratified aquifers can be achieved by either direct homogenization or inverse methods. In this paper, we propose a direct approach which leads to a simple closed form calculation of the effective conductivity tensor under certain assumptions of randomness, statistical anisotropy, statistical homogeneity, and ergodicity. The required data are of a statistical nature: single-point probability distribution of log-conductivity, and two-point covariance function or variogram of log-conductivity (principal directions and correlation scales). The proposed identification method is based on a fairly general, closed form expression for the three-dimensional effective conductivity tensor under the stated assumptions. This expression remains conjectural in the general case, but is confirmed by other results for several special cases of interest (reduced dimensions, gaussian distribution of lnK, etc.). The method is applied to available field data involving gaussian as well as non-gaussian log-conductivity fields. Limitations due to finite scale effects, geological inhomogeneity, and flow inhomogeneity, are discussed as well.

about the authors...

Joost C. Herweijer has a MSc in hydrogeology and geophysics from the Free University of Amsterdam. His academic interest was characterization of heterogeneous aquifers and application of solute transport models. After graduation (1983), he worked two years as a data processing consultant mainly in petroleum engineering projects. He joined Royal Dutch Shell as a research petroleum geologist, working and publishing on probabilistic facies modelling and sedimentological application of high resolution geophysical (diameter) well logs. Since October 1988, he has been employed with GeoTrans, working on a variety of research and operational projects in the field of ground water remediation.

Steven C. Young received his BA in environmental sciences from the University of Virginia and his MS in civil engineering from Stanford University. During the past seven years, Mr. Young has worked with the Tennessee Valley Authority to improve methods for characterizing the hydraulic properties of aquifers and for the applying of computer models to solve ground water related problems. His research experience includes the design and analysis of aquifer pump tests, artificial and natural gradient three-dimensional tracer tests, borehole flowmeter tests, small-scale evaporation experiments, water budget measurements of ash landfills, and studies to evaluate the EPRI's FASTCHEM model.

Mailing addresses:

Joost C. Herweijer
GeoTrans Inc.
250 Exchange Place, Suite A
Herndon, Virginia
22070, USA

Steven C. Young
Tennessee Valley Authority
Engineering Laboratory
129 Pine Road
Norris, Tennessee
37828, USA

Use of detailed sedimentological information for the assessment of well tests and tracer tests in a shallow fluvial aquifer

J.C. Herweijer and S.C. Young

Solute flow and transport models, used for the evaluation and management of ground water remediation, would largely benefit from information on heterogeneous hydraulic properties. In the current practice of well test interpretation, the non-ideal shape of individual drawdown curves, containing valuable information on heterogeneity, is often neglected. Interpretation of such non-ideal drawdown curves combined with soft information from a sedimentological facies model is demonstrated using field data from a 37 well network, developed for an 8 m thick aquifer in a one hectare test site. The site is located in an alluvial valley filled with fluvial sands, deposited during the Pleistocene and Holocene in an environment developing from braided to meandering streams.

Using a highly sensitive borehole flowmeter during a single well test, vertical profiles of localized hydraulic conductivity were determined at each well. To determine average hydraulic conductivities representing different scales, multiple well aquifer tests were conducted at different pumping rates. Finally, tracer tests were performed to determine preferential paths and travel times. For the interpretation, a model was chosen of high hydraulic conductivity active meandering channel deposits, discontinuous lenticular braided stream bar deposits, medium conductivity pointbar deposits, and low conductivity sheets of overbank deposits.

For actual simulation of flow and transport a stochastic procedure is proposed to randomly generate conductivities of grid cells, as an efficient alternative to conditional simulation based on a covariance structure (variogram). The initial grid cell dimensions reflect assumed dimensions for the elements of the sedimentological model. To obtain a correct numerical representation, grid refinement is required. Conductivities for initial grid cells can be drawn from any distribution based on field observations, and a predetermined trend is included. It is shown that variograms derived from such a grid concur with variograms as observed in the field.

about the authors...

Steven C. Young received his BA in environmental sciences from the University of Virginia and his MS in civil engineering from Stanford University. During the past seven years, Mr. Young has worked with the Tennessee Valley Authority to improve methods for characterizing the hydraulic properties of aquifers and for applying of computer models to solve ground water related problems. His research experience includes the design and analysis of aquifer pump tests, artificial and natural gradient three-dimensional tracer tests, borehole flowmeter tests, small-scale evaporation experiments, water budget measurements of ash landfills, and studies to evaluate the EPRI's FASTCHEM model.

Dudley J. Benton received his BS (focussing on fluid mechanics) and BS (focussing on offshore heat exchanger analysis) in ocean engineering from Florida Atlantic University, and a PhD in mechanical engineering from the University of Tennessee, Knoxville. His areas of interest include heat and mass transfer, thermodynamics, fluid mechanics, computer programming, and numerical mathematics.

Joost C. Herweijer has a MSc in hydrogeology and geophysics from the Free University of Amsterdam. His academic interest was characterization of heterogeneous aquifers and application of solute transport models. After graduation (1983), he worked two years as a data processing consultant mainly in petroleum engineering projects. He joined Royal Dutch Shell as a research petroleum geologist, working and publishing on probabilistic facies modeling and sedimentological application of high resolution geophysical (diameter) well logs. Since October 1988, he has been employed with GeoTrans, working on a variety of research and operational projects in the field of ground water remediation.

Mailing addresses:

Steven Young and Dudley Benton
Tennessee Valley Authority
Engineering Laboratory
Norris, Tennessee
37828, USA

Joost C. Herweijer
GeoTrans, Inc.
250 Exchange Place, Suite A
Herndon, Virginia
22070, USA

Geostatistical evaluation of a three-dimensional hydraulic conductivity field in an alluvial terrace aquifer

Steven C. Young, Joost C. Herweijer and Dudley J. Benton

Extensive borehole flowmeter tests were performed at 37 fully-screened wells on one hectare of an alluvial terrace aquifer to characterize the three-dimensional hydraulic conductivity field. At each well location, approximately 24 hydraulic conductivity measurements were taken at 0.3 m vertical intervals. These hydraulic conductivity measurements indicate that the arithmetic mean, geometric mean, and the variance of the natural logarithm of hydraulic conductivity field is 0.26 cm/s, 0.032 cm/s, and 4.7 cm/s respectively. A data analysis shows that the hydraulic conductivity field is not log-normally distributed and has definite trends. These trends are supported by the location of a former river meander in a 1956 aerial photograph of the site and the results of one large-scale and fourteen small-scale tracer tests. Prior to the borehole flowmeter tests, the well locations were optimized with respect to geostatistical analysis with the aid of a computer program. In order to apply geostatistics, the original data set was detrended by several different types of polynomials. The different residual data sets were analysed with respect to their covariance structure, statistical properties, and correlation to the original data. Although the analyses showed very different results for the different residual data sets, no set of criteria could be established to determine which data set was the most appropriate for geostatistical analyses. The results show that in some heterogeneous aquifers, a significant obstacle to geostatistics is detrending the data. As a result, a considerable amount of uncertainty will accompany geostatistical analysis in these heterogeneous aquifers.

about the authors...

Saleem G. Ghori is a graduate student at the New Mexico Institute of Mining and Technology. He has a BS degree in petroleum engineering from UET, Pakistan and an MS degree in petroleum engineering from New Mexico Institute of Mining and Technology. His area of study while working toward his doctorate is the assessment of reservoir heterogeneity.

John P. Heller is a senior scientist at the Petroleum Recovery Research Center and Adjunct Professor of Petroleum Engineering at New Mexico Tech. He has performed research on enhanced recovery methods for a number of years, both with Mobil Oil Company and at the PRRC. Current interests include both the relation between reservoir heterogeneities and displacement, such as in this work with Saleem Ghori and research on the development of mobility control additives for the displacement of oil, particularly by dense carbon dioxide. Heller believes that the use of mathematical and geostatistical methods in reservour analysis should be justified on physical and geological grounds.

Mailing address:

PRRC/New Mexico Tech
Campus Station
Socorro, New Mexico
87801, USA

Determination of permeability heterogeneity from a field tracer test through an improved numerical method

Saleem G. Ghori and John P. Heller

This presentation concerns the study of the flow of a miscible tracer in various flooding patterns in a nonuniform permeability field. The flooding patterns considered are the five-spot pattern, the staggered line drive, the direct line drive, and the inverted seven-spot. A way to quantify the effects of both channeling (due to permeability heterogeneities) and mixing (due to dispersion) is presented. Also, a new numerical technique considers both convection and physical dispersion, and approaches the solution differently than do conventional finite difference methods. An equation of motion, containing both Darcy and dispersive terms, allows tracking of isoconcentration lines. This numerical method is stable and avoids any numerical dispersion. Numerical results show good agreement with the approximate analytical solutions for the special case of a homogeneous five-spot pattern.

Random permeability fields are generated by both the Source Point method (SPM) and the Fast Fourier Transform method. The SPM is modified so that an accurate correlation structure can be prespecified. Advantages and disadvantages of both methods are discussed. The desired random field of permeability can be obtained by adjusting two parameters: the correlation length and the variance in the generators.

The integrated output concentration profile depends strongly on channeling and, to a much smaller degree, on the dispersive mixing, with the latter represented by a dispersion coefficient. Channeling, caused by permeability heterogeneity, affects both the shape and the extent of the output concentration profile. A large amount of channeling in a single-layered reservoir can exhibit multiple peaks in the output concentration profile. To determine the permeability heterogeneity of a particular reservoir, a catalog of tracer production curves from synthesized field tracer tests is assembled. Comparison of these curves with the profile obtained in a real field tracer production test can give an estimate of the dispersivity, variability and correlation lengths of the permeability heterogeneity.

about the author...

Mary P. Anderson received a BA in geology from SUNY-Buffalo and a PhD in hydrology from Stanford University. She has been a professor of geology at the University of Wisconsin-Madison since 1975, where she is also affiliated with the Institute of Environmental Studies, the Water Resource Management Program and the Center for Limnology. She is the coauthor of a popular textbook on ground water modelling and is currently writing a second book on application of ground water models. Dr. Anderson has served on numerous national committees and published over fifty research papers.

Mailing address.

Department of Geology and Geophysics
University of Wisconsin-Madison
1215 W. Dayton Street
Madison, Wisconsin
53706, USA

Aquifer heterogeneity - a geological perspective

Mary P. Anderson

Recent efforts to quantify heterogeneity in aquifers have involved assumptions about the variability inherent in geological materials. Stochastic models invoke the assumption of stationarity whereby variability is assumed to be *spatially periodic*. Fractal models view heterogeneity in geological materials to be *self-similar*. Another more general viewpoint is one that accounts for all types of *evolving heterogeneity*

Delving into the geological literature in search of clues to quantifying heterogeneity in aquifers is both enlightening and frustrating. Conceptual models of the distribution of sediments in specific geological environments, so-called facies models, provide information about regional trends in lithology that presumably are reflected in the hydraulic conductivity distribution. These conceptual models suggest that there are definable regional trends in lithology, making the assumption of stationarity inappropriate at this scale. The literature also contains detailed descriptions of site-specific deposits at the scale of an outcrop. From the petroleum literature we can obtain site-specific descriptions at the core scale and find generic discussions about quantifying the permeability of small scale sedimentary structures such as cross-bedding. Yet, there is very little information in the literature of the kind needed for hydrogeological investigations of heterogeneity. This is partly due to fundamental philosophical differences in the use of facies models in sedimentology and the petroleum industry and the needs of hydrogeologists. Nevertheless, there are insights from the sedimentological literature that may be helpful in quantifying heterogeneity in aquifers. Selected examples are discussed from a hydrogeological perspective.

about the authors...

Erik Webb is currently a graduate student working toward a PhD in hydrogeology at the University of Wisconsin. His work (with Dr. Mary Anderson and Dr. Dave Michelson) is funded by a Department of Energy, Environmental Restoration and Waste Management Fellowship. Erik completed his BS degree in engineering geology at Brigham Young University in 1986 and an MS in hydrogeology at the University of Wisconsin-Madison in 1989. Previous research has included: modelling the interaction of Lake Michigan with a Silurian dolomite aquifer along the central shoreline of eastern Wisconsin; and mathematical modelling of heat flow through the crust of Io, a moon of Jupiter.

Mary P. Anderson received a BA in geology from SUNY-Buffalo and a PhD in hydrology from Stanford University. She has been a professor of geology at the University of Wisconsin-Madison since 1975, where she is also affiliated with the Institute of Environmental Studies, the Water Resource Management Program and the Center for Limnology. She is the coauthor of a popular textbook on ground water modelling and is currently writing a second book on application of ground water models. Dr. Anderson has served on numerous national committees and published over fifty research papers.

Mailing address:

Department of Geology & Geophysics
University of Wisconsin-Madison
1215 W. Dayton Street
Madison, Wisconsin
53706, USA

Using a sedimentary depositional model to simulate heterogeneity in glaciofluvial sediments

E.K. Webb and M.P Anderson

Glaciofluvial deposits usually consist of several depositional facies, each of which has different physical characteristics, depositional structures and hydraulic properties. Therefore, it is unlikely that the property of stationarity (a constant mean hydraulic conductivity and a monomodal probability distribution) holds for an entire glaciofluvial sequence. However, the process of dividing an outwash sequence into geological facies presumably identifies units of material with similar physical characteristics. Therefore, hydraulic conductivity or other hydraulic characteristics may exhibit the property of stationarity at the scale of a single facies unit.

It is proposed that patterns of geological facies determined by field observation can be quantified by mathematical simulation of sediment deposition. Subsequently, the simulated sediment distributions can be used to define the distribution of hydrogeological parameters, estimate the extent of stationarity, and locate possible 'fastest paths' for contaminant movement.

To test this hypothesis, a hypothetical glacial outwash deposit, based on geological facies descriptions contained in the literature, was simulated using the SEDSIM sedimentary depositional model to produce a three-dimensional description of sediment grain-size distributions. Grain-size distributions were then used to estimate the spatial distribution of hydraulic conductivity. Subsequently, a finite-difference code was used to simulate ground water flow through the hypothetical glacial outwash. This represents a first step in describing the spatial heterogeneity of hydrogeological characteristics for glaciofluvial and other braided stream environments.

about the authors...

John Kramers earned his BSc and MSc in geology from the University of Alberta and I PhD in geology from Rensselaer Polytechnic Institute. He is currently a senior research off with the Alberta Geological Survey, Alberta Research Council and project leader for the Reservoir Analysis Project. His current research interests include quantitative reservoir description and characterization.

Li-Ping Yuan earned his BSc in geology from the National Taiwan University in 1978, MSc in geological sciences from the University of Illinois and his PhD in geology from the University of South Carolina in 1987. He is currently an assistant research officer with the Alberta Geological Survey, Alberta Research Council and a member of the Reservoir Analy Project Team. His current research interests include image analysis of pore systems and computer applications in geology

Stefan Bachu has an engineering degree in hydraulics and a PhD in transport processes from the Technion-Israel Institute of Technology. He is presently Head of the Petroleum Geology and Basin Analysis Section of the Alberta Geological Survey. His main areas of interest are hydrogeological and geothermal processes in sedimentary basins, and scaling-up rock and fluid properties from core (lab) to basin scale.

Dave Cuthiell is a member of the Mathematical Modelling Group in the Oil Sands and Hydrocarbon Recovery Department of the Alberta Research Council. Dave received his Phl in physics from Cornell University in 1977. He has been with the Alberta Research Council since 1981; his current major interests are the modelling of geological heterogeneity for purposes of reservoir simulation and recovery mechanisms in steam-based enhanced oil recovery.

Mailing address:

Alberta Geological Survey
Alberta Research Council
PO Box 8330, Station F
Edmonton, Alberta
T6H 5X2, Canada

Reservoir characterization case study: sandy facies

J.W. Kramers, L.-P. Yuan, Stefan Bachu and David Cuthiell

The Provost Upper Mannville B Pool in east central Alberta is contained in McLaren Formation sands of Lower Cretaceous age. The reservoir provides an ideal case study for developing reservoir characterization techniques, because several scales of heterogeneity are present and because there is a high density of wells, with excellent core and a suite of modern geophysical well logs. The reservoir is up to 35 m thick and original oil in place has been estimated at 34,200,00 m^3 of 13° API oil. Wells in the reservoir have primary production and several EOR projects are or have been active in the pool.

The reservoir sands were deposited in fluvial environments in a valley fill setting. It consists of an overall fining upward sequence and can be divided into a lower blocky channel lithofacies, making up most of the reservoir, grading up through a transition zone lithofacies into a channel margin lithofacies. This, in turn, is overlain by overbank and abandonment lithofacies. Within the blocky channel lithofacies is a shale clast lithofacies, comprising extremely heterogeneous zones of shale breccia in a sand matrix. The reservoir can be divided into two main portions, a sandy part and a heterogeneous part. Petrophysical properties, such as permeability, can be defined for each of these using different techniques. The sandy portions were characterized using statistical averaging of core analysis results on a well and pool wide basis, combined with results of pore type definition using petrographic image analysis techniques. As a result, four flow units were recognized in the sandy portion of the reservoir: the water saturated blocky channel sands, the oil saturated blocky channel sands, the transition zone sands, and the channel margin sands. Measured capillary pressure curves and residual saturations were qualitatively correlated with pore types and their characteristics. Thus, the characterization for each of the flow units produces the data at the scale required for numerical process simulation.

about the authors...

Stefan Bachu has an engineering degree in hydraulics and a PhD in transport processes f the Technion-Israel Institute of Technology He is presently Head of the Petroleum Geology Basin Analysis Section of the Alberta Geological Survey. His main areas of interest are hydrogeological and geothermal processes in sedimentary basins, and scaling-up of rock and properties from core (lab) to basin scale.

Dave Cuthiell is a member of the Mathematical Modelling Group in the Oil Sands and Hydrocarbon Recovery Department of the Alberta Research Council. Dave received his PhD physics from Cornell University in 1977. He has been with the Alberta Research Council sin 1981, his current major interests are the modelling of geological heterogeneity for purposes o reservoir simulation and recovery mechanisms in steam-based enhanced oil recovery.

John Kramers earned his BSc and MSc in geology from the University of Alberta and hi PhD in geology from Rensselaer Polytechnic Institute. He is currently a senior research offic with the Alberta Geological Survey, Alberta Research Council and project leader for the Reservoir Analysis Project. His current research interests include quantitative reservoir description and characterization.

Li-Ping Yuan earned his BSc in geology from the National Taiwan University in 1978, h MSc in geological sciences from the University of Illinois and his PhD in geology from the University of South Carolina in 1987 He is currently an assistant research officer with the Alberta Geological Survey, Alberta Research Council and a member of the Reservoir Analys Project Team. His current research interests include image analysis of pore systems and computer applications in geology.

Mailing address:

Alberta Geological Survey
Alberta Research Council
PO Box 8330, Station F
Edmonton, Alberta
T6H 5X2, Canada

Reservoir characterization case study: bimodally heterogeneous facies

Stefan Bachu, David L. Cuthiell, John W. Kramers and Li-Ping Yuan

Shale clast zones are common in channel deposit reservoirs and have a potentially large impact on oil recovery operations. These zones are similar in their properties and behaviour to sand-gravel aquifers. These reservoirs and aquifers possess a bimodal type of heterogeneity with a large permeability contrast between the sand and the shale clasts or gravel. Proper characterization and scaling-up of reservoir/aquifer properties are fundamental in the study of fluid flow and transport processes in such cases. The effect at the core scale of this bimodal heterogeneity on absolute permeability was studied for two-dimensional flow using numerical simulations with actual reservoir data, and for three-dimensional flow using physical experiments.

The two-dimensional flow study is based on a data set of approximately 7000 digitized shale-clast outlines taken from 20 m of cores in three different wells from the Provost Upper Mannville B Pool, a reservoir situated in the heavy-oil belt of east-central Alberta. The flow simulations through 16 core-size regions containing between 10 and 49% shale clasts by area show that the effective permeability depends mainly on the heterogeneity fraction and permeability contrast, a dependence which can be expressed by a generalized weighted-mean model. The presence of the shale clasts in the isotropic sand matrix creates anisotropy at the larger scale, due mainly to the predominantly flat shape and subhorizontal orientation of the clasts.

Physical experiments were performed on synthetic 'shale-clast' systems comprised of pebbles set in a sand matrix. The sand-pebble systems, having dimensions of 20x20x20 cm, were thermally consolidated using a special resin-coated sand. After the physical experiments were performed, the sand-pebble cubes were sliced, and the two-dimensional images of the slices were used in two-dimensional numerical flow simulations. Three-dimensional flow simulations could not be performed because of data and computer limitations. The results show that the effective permeability is significantly reduced in both two and three dimensions because of the clasts' presence, but, surprisingly, only to a slightly lesser degree in three-dimensional flow.

about the authors...

Rick Stebnisky is a senior hydrogeologist at J.B. Butler and Associates, Inc., an environmental consulting firm in Tampa, Florida. He has designed, executed and managed a variety of hydrogeological investigations primarily concerning water resources development and related impacts and ground water and soil contamination and remediation. He received a BS in geology from Edinboro University of Pennsylvania (1983) and a MS in geology from the University of South Florida, Tampa (1987). His primary research interest is in evaluation of aquifer characteristics and water resources of islands and coastal environments.

Len Vacher is an associate professor of geology at the University of South Florida, Tampa. He received a BS in geology from the University of Washington and MS and PhD degrees in geology from Northwestern University, and came to Florida after nine years at Washington State University. His research interests involve mainly Pleistocene sea-level history, hydrology of ocean islands, and meteoric diagenesis of carbonates. He and his students work mainly in the Florida Keys, Bahamas and Bermuda.

Mailing addresses:

Richard J. Stebnisky
J.B. Butler & Associates, Inc.
PO Box 23526
Tampa, Florida
33623, USA

H. Leonard Vacher
University of South Florida
4202 Fowler Avenue
Tampa, Florida
33620, USA

Hydraulic conductivity predicted as a function of grain size, sorting and porosity for dune, washover and foreshore depositional environments on a barrier island in Florida, USA

Richard J Stebnisky and H. Leonard Vacher

Permeameter analysis of 90 undisturbed, triaxially oriented sediment cores indicates that sediments recently deposited on Anclote Key, a west-central Florida barrier island, are heterogeneous and isotropic with respect to hydraulic conductivity (K). Statistical analyses show that factors affecting K are complex and interrelated. Mean grain size is the only variable affecting K consistently for all three depositional environments (dune, washover and foreshore) and the total data set. Overall, statistical correlations suggest that K increases with mean grain size, porosity, packing proximity, improved sorting, and as skewness becomes more positive. For any single variable, these correlations generally are weak and account for only a small percentage of the variance. Hydraulic conductivity, therefore, seems to be best described by a multivariate function.

The Kozeny-Carman equation was modified to incorporate a grain-sorting factor patterned after the Krombein-Monk equation. For the fine-grained, very well-sorted sands of this study, the modified equation predicts K values that average only 1% lower than permeameter measurements of K for the 7 major data groups, and 1% higher than permeameter measurements of K when considering each of the 30 triaxial samples. These data indicate that K values for any given sample can be predicted to within ± 30% of its measured value, with 95% confidence, by:

$$K = [450\, d_m^2]\, [n^3/(1-n)^2]\, [e^{-S_\phi}]$$

where K is hydraulic conductivity (cm/s); d_m is mean grain diameter (cm); n is porosity (fraction); and S_ϕ is the phi sorting coefficient. This empirical relationship expresses K as a product of a size-shape factor, a porosity factor, and a sorting factor.

This equation is suggested for purposes of estimating hydraulic conductivity for unconsolidated sands from beach-related environments. Values for the necessary variables can be obtained easily and inexpensively by routine laboratory analysis of sediments.

about the authors...

Fred G. Baker is Manager of Hydrogeologic Services for Woodward-Clyde Consultants in Denver, Colorado. He obtained a BS in geology and an MS in soil science at the University of Wisconsin-Madison, and an MS in civil engineering and PhD in geology at the University of Colorado-Boulder. His areas of interest include ground water flow and solute transport under saturated and unsaturated conditions, mass transport modelling, in situ and laboratory testing of aquifer and soil transport properties. He has been actively involved in research and consulting for 15 years.

Hannah F. Pavlik is Leader of the Geochemistry Group for EBASCO Environmental in Denver, Colorado. She obtained her PhD in geochemistry at the University of Colorado. Her areas of expertise include aqueous geochemistry, rock/water interactions and solute mobility and transport. She has more than ten years of experience in consulting and university research.

Mailing addresses:

F.G. Baker
Woodward-Clyde Consultants
4582 S. Ulster St. Pkwy
Denver, Colorado
80237, USA

Hannah F. Pavlik
EBASCO Environmental
143 Union Boulevard
Lakewood, Colorado
80228-1824, USA

Characterization and modelling of ground water flow in a heterogeneous aquifer system to evaluate contaminant migration

F.G. Baker and H.F. Pavlik

The hydrogeological regime and extent of ground water contamination were characterized at a federal Superfund site in the Sacramento River valley of northern California. Wood preserving compounds, primarily pentachlorophenol (PCP) and creosote have been detected in the soil and ground water. A plume of dissolved PCP up to approximately 1.5 miles long has been identified in ground water south of the plant.

Aquifer heterogeneity is dominated by the juxtaposition of channel-fill gravel and sand facies against less permeable flood plain clays and debris-flow units which act as aquitards. The aquifer consists of a complex multizonal system of permeable gravels and sands composed of units from four geological formations deposited by the ancestral Feather River. Fluvial channel gravels form the principal aquifer zones and contain overbank clay and silt deposits which locally form clay lenses or more continuous aquitards. Two incised paleo-channels of the Laguna Formation are inset into the older Mehrten Formation near the site, complicating the aquifer stratigraphy. The geometric mean horizontal hydraulic conductivities for channel gravels range between 120 to 530 ft/d. Mean vertical aquitard hydraulic conductivity is 0.07 ft/d. Ground water flow is generally southward with a velocity ranging from 470 to 1000 ft/a. Ground water flow is largely advection-dominated in this system.

The spatial distribution of dissolved PCP in the aquifer documents the interactions between major permeable zones. Hydrostratigraphic evidence pointing to the separation of aquifer zones is supported by the major ion chemistry of ground water. The sodium and calcium-magnesium bicarbonate-rich water present in the upper aquifer zones is significantly different in chemical composition from the predominantly sodium chloride-rich water present in the deeper permeable zone. This indicates that hydrodynamic separation exists between the upper and lower zones of the aquifer, limiting the vertical movement of the PCP plume. A 3-D numerical ground water model, based on the conceptual hydrogeological model described here was developed for use as a tool for design of a ground water extraction and treatment system.

about the authors...

David G. Thomson is a contaminant hydrogeologist in the Environmental Research and Engineering Department at the Alberta Research Council. He received a BSc in civil engineering from Queen's University, Kingston and a MSc in hydrogeology from the University of Waterloo in 1990. Between 1981 and 1986 he worked in Africa and Canada as a petroleum engineer. Since 1988, his primary research interests have been hydraulic response of fractured tills and numerical analysis of transport in porous media.

John A. Cherry is Director of the Institute for Groundwater Research at the University of Waterloo and a professor in the Department of Earth Sciences. He is coauthor with Allen Freeze of the textbook "Groundwater", published in 1979. Dr. Cherry has been involved in the study of ground water contamination associated with waste disposal since 1968. His research interests have focused on processes of contaminant migration in ground water and field investigations of waste disposal and spill sites across Canada.

Mailing addresses:

David G. Thomson
Environmental Research and
Engineering Department
Alberta Research Council
PO Box 8330, Station F
Edmonton, Alberta
T6H 5X2, Canada

John A. Cherry
Department of Earth Scien...
University of Waterloo
Waterloo, Ontario
N2L 3G1, Canada

Hydraulic evidence of Wisconsinan-aged open fractures in a deep clayey till

David G Thomson and John A. Cherry

Most investigations of fracturing in clayey glacial till have been limited to shallow weathered deposits. This paper presents the results of an investigation of fracturing in a clay till 60 m below ground level. A detailed vertical profile of hydraulic response in a thick clay till aquitard was recorded with pressure transducers during a 25-day pumping test. The field response was analysed with analytical solutions to determine the bulk hydraulic conductivity The presence of open fractures was confirmed on the basis that the bulk hydraulic conductivity of fractured clayey till is two orders of magnitude greater than its matrix hydraulic conductivity. A three-dimensional analysis of in situ drawdowns indicates that the spacing between fractures ranges between 1.2 m and 5 m. Geological evidence suggests that the fractures were formed during Wisconsinan time, and have remained open through at least one subsequent glacial advance.

about the authors...

Baoren Chen was educated in the People's Republic of China at the Beijing Geological Institute, majoring in hydrogeology and engineering geology. He is currently with the Department of Earth Sciences, Nanjing University, conducting research on the frequency character and transfer function of ground water hydrograph and teaching a course on the ground water regime and its forecast.

Mailing addresses.

Baoren Chen
Department of Earth Sciences
Nanjing University
Nanjing, Jiangsu 210008
People's Republic of China

Peikang Jin
The Nanjing Institute of Hydrology
The Ministry of Water Resources
Nanjing 210024
People's Republic of China

The spectrum features of deep water-bearing systems and research of transfer function

Baoren Chen and Peikang Jin

The fluctuation of most hydrographs in deep wells record the fluid pulsations in the lithosphere and variation of the Earth's crust. Many observations have verified that ground water is the ideal information carrier of the crust.

In this paper, the series of input (precipitation, air pressure, Earth tide, etc.) and output (water table, artesian flow) of deep aqueous systems are studied by using the spectrum analysis and system theory The application of the concepts of transfer function and the spectrum structure of the hydrograph enrich the knowledge of the deep aqueous system.

Two typical spectrum structures of hydrographs of deep aqueous systems are obtained by comparing with many water-bearing systems of the Ji Zhong Sea. One is from z Ma-17 well and another is from the Xing Zhe-5 well.

Finally, the physics models of forming the spectrum of the hydrograph are constructed on the basis of spectrum research of the deep aqueous system.

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about the authors...

Leslie Smith is a professor of Geological Sciences at the University of British Columbia in Vancouver. He has conducted research in the areas of solute transport in heterogeneous porous media, transport processes in fractured rocks, the influence of ground water flow on the Earth's thermal regime, and the role of ground water in geodynamic processes.

Tom Clemo is a PhD student at the University of British Columbia on leave from the Idaho National Engineering Lab. He holds degrees in mechanical engineering from the University of California, Davis and in nuclear engineering from the University of California, Berkeley.

Mark Robertson is a MASc student at the University of British Columbia. He holds a degree in geological engineering from the University of British Columbia.

Mailing address:

Department of Geological Sciences
University of British Columbia
Vancouver, British Columbia
V6T 2B4, Canada

New approaches to the simulation of field-scale solute transport in fractured rock masses

Leslie Smith, Tom Clemo and Mark Robertson

Predictions of rates and patterns of solute transport in geological media where fractures provide the dominant pathways for fluid flow present hydrogeologists with a complex problem for which conventional transport models may not be well-suited. Two methods are described with the view to developing a simulation capability when the length scale of interest is on the order of hundreds of metres or more. Both approaches are founded on statistical data from mapping of the geometric properties of fracture sets. The first method, a statistical continuum approach, is applicable in the case where it is possible to identify, at the scale of interest, representative volume-averaged properties describing the transport process. Anisotropic dispersion in a network of finite-length, randomly-located fractures of variable aperture is modelled by first collecting statistics on particle motion in a discrete subdomain model, and then using these statistics to model transport at a larger scale using continuum approximations. The second method, called the dual permeability approach, is designed to handle the case of a fracture system where there are multiple scales of fracturing, a situation where a representative volume may not be definable. It combines features of both discrete fracture and continuum models. Dominant fractures that contribute significantly to fluid flux are preserved as discrete features, smaller scale fractures are submerged into continuum blocks. Mass transfer across continuum blocks is expressed in terms of transition probabilities on travel time and on exit location to a down-gradient discrete fracture. Porous medium equivalency is not assumed for the continuum blocks. The transition probabilities are calculated from the statistical parameters of the smaller-scale fracture sets, the orientation of the local hydraulic gradient, and the location of larger-scale discrete fractures which define the geometry of continuum blocks. In both of these approaches, it is possible to simulate solute transport on length scales that exceed the feasible limit of discrete fracture simulation, while preserving the unique influence of the geometry of the fracture network on the transport process.

about the authors...

Peter S. Baker is a senior geologist for C-E Environmental Inc. He has ten years experience in the fields of geology, hydrogeology, and geophysics. For the last five years he has been involved in a wide range of remedial investigations and feasibility studies. His main focus recently has been the characterization and remediation of contaminated bedrock aquifers. He is a Certified Professional Geologist in the state of Maine.

Willard A. Murray is a senior consultant for C-E Environmental Inc. He has twenty years of experience in the fields of hydrogeology and hydraulic engineering. He has been responsible for surface water quality and quantity studies and hydrogeological investigations to assess contaminant migration, and the design of remedial measures for uncontrolled hazardous waste sites. Dr. Murray has also held positions as Western Region Coordinator of Waste Management Services for Dames and Moore in San Francisco; Chief Groundwater Hydrologist for Haley and Aldrich, Inc. in Cambridge, Massachusetts. He is a Registered Professional Engineer in the states of Maine, Pennsylvania, Florida and California.

Mailing address:

C-E Environmental Inc.
261 Commercial Street
PO Box 7050
Portland, Maine
04112, USA

Use of pumping test data to determine radial and non-radial flow zones in a fractured limestone aquifer

P.S. Baker and W.A. Murray

A product recovery/pumping test was conducted at a gasoline contaminated site to determine the hydraulic characteristics of a fractured bedrock aquifer so that remedial measures to remove a layer of floating product could be designed, and the feasibility of ground water a "pump and treat" action could be assessed. The aquifer of concern consists of metamorphosed limestone with the water table 20 feet below the bedrock surface. The development of the drawdown cone in response to pumping revealed the degree and direction of fracture anisotropy. The evaluation of semi-log and log-log plots of drawdown versus time for the pumping and observation wells indicates the presence of both non-radial flow and radial flow response zones. The water level response to pumping in one observation well shows an inertial oscillation effect and that is indicative of a high degree of hydraulic connectivity with the pumping well. Curve matching data from this well and the pumping well indicates the presence of non-radial flow conditions and a delayed yield response in the vicinity of a primary fracture zone, and provides an estimate of the transmissivity of this feature. The orientation of this primary fracture feature agrees with the orientation of the elliptical drawdown cone that developed during pumping. The water level response in several observation wells exhibit radial flow behaviour and a double porosity response. The synthesis of these interpretations indicates a vertically fractured, anisotropic, bedrock aquifer with greatest transmissivity in a northwest-southeast direction along the primary fracture zone and primary storage in the secondary fissures. The ratio of ground water/product flow to the pumping well was large, indicating a lack of horizontal fracturing and a low transmissivity normal to the primary fracture feature.

about the authors...

Brian Berkowitz is a research hydrologist with the Hydrological Service of Israel. He completed his BSc and MSc in applied mathematics at the University of Alberta and his DSc at Technion, Israel. He was awarded the Israel Hydrology Association Goldschmidt Prize in 1986. His major areas of interest include flow and contaminant transport in fractured porous media, and dispersion phenomena in porous media.

Isaac Balberg is a professor of physics at the Racah Institute of Physics, Jerusalem. He holds MSc and PhD degrees from the Hebrew University. During 1970-72 and 1979-80 he was a member of the technical staff at RCA Laboratories, Princeton. He has been a senior scientist in many research institutions and laboratories from 1974 to date. He is currently acting as secretary of the Israel Physical Society. His field of interest is transport in disordered media.

Mailing addresses:

Brian Berkowitz
Hydrological Service
Water Commission
Ministry of Agriculture
PO Box 6381
Jerusalem 91063, Israel

Isaac Balberg
The Racah Institute of Physics
The Hebrew University of Jerusalem
Jerusalem 91904, Israel

A percolation model for hydraulic conductivity in porous media

B. Berkowitz and I. Balberg

While percolation theory has been studied extensively in the field of physics, and the literature devoted to the subject is vast, little use of its results has been made to date in the field of hydrology. The principal advantage of percolation theory is that it provides universal laws which determine the geometrical and physical properties of the system. These laws are usually manifested by a power-law behaviour of the type $A \propto (v-v_c)^x$, where A is a geometrical or physically observable quantity, v is the fractional volume of the conducting phase, v_c is the critical value for the onset of percolation, i.e., system connectivity, and x is an exponent specific to this quantity. In the present study, we carry out Monte Carlo computer simulations on a percolating model representative of a porous medium. The model considers intersecting conducting permeable spheres (or circles, in two dimensions) which are randomly distributed in space. The local geometry of the intersection between two permeable spheres may or may not determine the local conductance. Therefore, three cases are considered: (1) all intersections have uniform conductivity, (2) conductivities are drawn from a log-normal distribution, and (3) conductivities are determined by the degree of overlap of the intersecting spheres. It is found that the critical behaviour of the hydraulic conductivity of the system, K near the percolation threshold, follows a power-law dependence defined by $K \propto (v/v_c-1)^{-t}$, where t is an exponent which depends on the dimensionality and the case. For example, all three cases yield a value of $t \sim 1.3$ in the two-dimensional system, while $t \sim 2.0$ is found in the three-dimensional system for only the first two cases. In the third case, $t \sim 2.5$. These results are in agreement with the most recent predictions of percolation theory. We can thus see that percolation theory provides useful predictions as to the structural parameters which determine hydrological transport processes.

about the authors...

Eileen Poeter is an assistant professor of Geological Engineering at the Colorado School of Mines, Golden, Colorado. She received her BS degree in geology from Lehigh University in 1975 and her MS and PhD degrees in engineering (specializing in ground water and geophysics) from Washington State University in 1978 and 1980, respectively She has worked in consulting and academics. Her research is focused on characterization of aquifer heterogeneity as it relates to contaminant transport and site remediation.

Peter Townsend is a Masters degree candidate at the Colorado School of Mines. He received his BS degree in geological engineering in 1987 from Washington State University. Peter worked in geotechnical consulting before returning to school to study ground water.

Mailing address:

Colorado School of Mines
Golden, Colorado
80403, USA

Delineating aquifer heterogeneity with stochastic multiple indicator conditional simulation of the unconfined aquifer, Hanford Site, Washington, USA

Eileen Poeter and Peter Townsend

Spatial variability of heterogeneities is estimated in a portion of the unconfined aquifer on the Hanford Site, Richland, Washington. Multiple, equiprobable realizations of heterogeneity for the domain of interest are generated using an indicator conditional simulation technique These multiple realizations are scanned to produce conditional probability and spatial connectivi y maps of individual facies. The result of this work is an estimate of spatial variability of hydrofacies from limited data with emphasis on assessment of continuous high hydraulic conductivity units.

Facies with similar hydraulic properties (hydrofacies) are identified based on grain size data from borehole samples using factor and cluster analysis. A range of hydraulic conductivities (based on field tests and sediment character), and an indicator value (0,1,2,3, etc.) is assigned to each sediment group. Nested variogram models are used to account for spatial continuity of each hydrofacies in the stochastic simulations. Numerous, equiprobable realizations provide a measure of uncertainty of the distribution of sedimentological units which reflect the distribution of ground water flow and contaminant transport properties. Use of multiple, equiprobable realizations of aquifer heterogeneity as input to a flow and transport model produces a frequency distribution of hydraulic heads and contaminant concentrations that can be used to assess risks and aid management decisions. Ultimately, inverse techniques will be employed to thoroughly integrate known field conditions in estimates of flow and transport parameters within each stochastic realization, thus, further constraining interpretation of the system.

about the author...

Elizabeth A. Jacobson received her BA in math and physics from California State University, San Bernardino, an MS degree in atmospheric physics from the University of Arizona and a PhD in hydrology at the University of Arizona. In 1983 she joined the Hydrology Section of the Geosciences Deparptment at Battelle Pacific Northwest Laboratories. In 1988, Dr. Jacobson joined the Water Resources Center of the Desert Research Institute, University of Nevada as Assistant Research Professor. She also teaches graduate level courses at the University of Nevada.

Dr. Jacobson specializes in the development and improvement of parameter estimation (inverse) methodology as it applies to ground water flow problems. She maintains an active research interest in geostatistics and kriging, conditional simulation, and sensitivity and uncertainty techniques as they apply to ground water systems.

Mailing address:

Water Resources Center
Desert Research Institute
University of Nevada
Reno, Nevada
89506-0220, USA

Investigation of the spatial correlation of saturated hydraulic conductivities from a vertical wall of a trench

Elizabeth A. Jacobson

Stochastic flow and transport theories require an estimate of the covariance functions for the hydrologic properties. Estimating a covariance function based on the data for the complete flow region will yield correlation lengths and a variance that are "averaged" values. However, different correlation lengths and variances may be contained in the region of interest, which may influence the comparison of actual field data to the predictions of stochastic flow and transport theories.

A two-dimensional data set of saturated hydraulic conductivity was obtained from a trench at New Mexico State University. The saturated hydraulic conductivity data were measured in situ using a Guelph permeameter along a vertical wall of the trench, which measured 26.4 m in length and 6.0 m in depth. Five hundred and eighty-eight saturated hydraulic conductivity (K_s) values were obtained from nine distinct soil horizons and three vertical transects. The logarithms of the in situ saturated hydraulic conductivities were analysed using directional semi-variograms to estimate the variance, the correlation lengths, and the principal directions. The first analysis assumed that the ln K_s data had a constant mean and variance, and horizontal and vertical correlation lengths were estimated based on the entire two-dimensional data set. The second analysis consisted of grouping the ln K_s data from several horizons or all vertical transects into separate data sets and estimating the corresponding variance and correlation lengths. Data for different horizons were grouped based on similar means and variances. The estimated horizontal and vertical correlation lengths for the first analysis differed from the values obtained for the second analysis. The variations in correlation lengths are discussed with regard to expected spatial correlation based on geological descriptions of the various horizons and expected effects on flow and transport. In addition, a brief comparison of the semi-variogram approach and spectral analysis approach for estimating spatial correlation is included.

about the authors...

Kevin K. Wolka received a BS in civil engineering in 1972 and an MSCE in Water Resources Systems in 1974 from Purdue University. After working for engineering consulting firms in Chicago and Minneapolis-St. Paul, he joined the Iowa State University Civil Engineering Department in 1980. In 1986, he received his PhD in water resources from Iowa State University. His current research interests include stochastic analyses of ground water contamination processes

Dr. T. Al Austin is Professor of Civil and Construction Engineering and Director of the Water Resources Research Institute at Iowa State University. He received his BSc and PhD degrees from Texas Tech University and his MSc from Utah State University. Dr. Austin joined the faculty at Iowa State University in 1972 and has had extensive research work in water resources, hydrology and ground water hydrology since coming to ISU. In recent years, Dr. Austin has worked in modelling ground water transport processes. He has supervised seven PhD and more than 30 MSc student research theses.

Mailing addresses:

Kevin K. Wolka
Geraghty and Miller, Inc.
50 West Big Beaver Road
Troy, Michigan
48084, USA

T. Al Austin
Department of Civil and
Construction Engineering
Iowa State University
Ames, Iowa
50011, USA

Stochastic modelling of contaminant movement in ground water

Kevin K. Wolka and T. Al Austin

A stochastic procedure is described for use in a ground water contamination exposure assessment. This procedure delivers more information about contaminant movement than single solution numerical or analytical solute transport models. Multiple solutions for contaminant movement are used to develop a probability distribution of results. The stochastic nature of this exposure assessment procedure is derived primarily from the spatial variability of hydraulic conductivity in geological formations and its effect on the uncertainty of contaminant movement in ground water. The Turning Bands Methods is used along with a deterministic random walk solute transport model developed by the Illinois State Water Survey to form a "joint probability distribution of contaminant concentration and duration of exposure".

The field data used in the modelling effort represent injections of low level radioactive wastes (tritium) from the Idaho Chemical Processing Plant (Idaho National Engineering Laboratory) into the Snake River Plain aquifer. Over 30 years of data, including injection flow rates and concentrations, and monitored well water levels and concentrations, were provided by the Idaho District of the US Geological Survey, together with a transmissivity map of the Snake River Plain aquifer at the INEL.

The spatial variability of hydraulic conductivity is a major cause of uncertainty for contaminant movement in ground water. The Turning Bands Method aids in quantifying the uncertainty by generating a specified number of hydraulic conductivity fields, each to be used as input to the solute transport model for a contaminant movement realization. Every one of the hydraulic conductivity fields is unique, but they all have the same statistical properties, i.e., mean, standard deviation and correlation function. Each hydraulic conductivity field results in a corresponding unique contaminant movement pattern. The aggregation of these contaminant movement patterns results in the aforementioned "joint probability distribution".

The existing transmissivity study area has a mean hydraulic conductivity log value of 2.4427 and a standard deviation of 0.1226 in metric units. The correlation function is $r = e^{-0.904d^2}$, where r is the correlation coefficient and d is the distance in km between two points in the aquifer. The computer model generated hydraulic conductivity fields with means within 1% to 2% of the input mean, and standard deviations approximately 15% from that entered. The joint probability distribution of contaminant concentration and duration of exposure stabilized after 100 realizations with the solute transport model for two separate tritium disposal events. A statistical description of the joint probability distributions was obtained using the logit transformation.

about the authors...

Geoffrey Bohling earned a BA in english and a BSc in physics-geophysics from the University of Kansas in 1986. He received an MSc in geology with a major in hydrogeology from the University of Wisconsin-Madison in 1988. He is now a research assistant in the Advanced Projects Section of the Kansas Geological Survey. Mr Bohling is pursuing research on sensitivity analysis in aquifer parameter estimation and participating in various projects involving mathematical and statistical applications in geology.

Jan Harff is a geologist from the German Democratic Republic and has spent the 1989 spring semester as a visiting research scientist at the Kansas Geological Survey. Dr. Harff received his geological training at Humboldt University in Berlin and Arndt University in Greifswald, where he earned his doctorate in 1974. The GDR Academy of Science awarded him the DSc in 1986 when he also received the A.G. Werner medal. He was the 1989 recipient of the Academy's Stammberger Prize. In Potsdam, Dr. Harff is Chief of the Mathematical Geology Department of the Central Institute for Physics of the Earth.

John C. Davis received his PhD in geology from the University of Wyoming in 1967. Currently he is Senior Scientist and Advanced Projects Section Chief at the Kansas Geological Survey and Professor of Chemical and Petroleum Engineering at the University of Kansas. Dr. Davis authored "Statistics and Data Analysis in Geology", coauthored "Display and Analysis of Spatial Data" and "Probability Methods in Oil Exploration", contributed to 15 other texts and compendiums, and authored/coauthored over 90 scientific articles and reviews. He served as President of the International Association of Mathematical Geology from 1984-1989 and was awarded their Krumbein Medal in 1987.

Mailing addresses:

Geoffrey Bohling and John C. Davis
Kansas Geological Survey
1930 Constant Avenue
The University of Kansas
Lawrence, Kansas
66047, USA

Jan Harff
Akademie der Wissenschaften der DDR
Zentralinstitut fur Physik der Erde
DDR-1561
Potsdam, German Democratic Republic

Regionalized classification: ideas and applications

Geoffrey C Bohling, Jan Harff and John C. Davis

Regionalized classification involves mapping the results of a multivariate classification of a set of observations onto the physical space from which the observations were taken. The process identifies optimal boundaries between physically contiguous regions which are homogeneous in the statistical properties of the observations within them. It is also possible to produce a map of the probability of correct classification. The probability is high in the centers of the identified regions and lower at the boundaries between regions. The sharpness of the probability transitions at regional boundaries indicates both the degree of heterogeneity in the boundary regions and the uncertainty in placement of the boundaries.

The process can be applied to any set of observations on a number of variables measured at different points in space. An obvious application to hydrogeology and reservoir engineering would use regionalized classification to determine optimal zonation of a flow and/or transport model with spatially distributed parameters. Regionalized classification is especially promising for problems in which a particular variable (such as aquifer transmissivity) is of primary interest, but there are relatively few observations of this variable in the data set. The multivariate classification can be based on the limited number of observations for which the variable of interest is measured. The entire set of observations can then be assigned to classes using a more widely available subset of the variables used in the classification process. Alternatively, the classification can be made using a subset of variables which are strongly correlated with the variable of interest.

A regionalized classification of stratigraphic data from western Kansas is presented as an example of the procedure. Although the study is designed to identify regions of high oil production, the principles apply to a wide range of problems in hydrogeology and reservoir engineering.

about the authors...

John L. Wilson is Professor of Hydrology and Director of the Hydrology Program at the New Mexico Institute of Mining and Technology. He is a BCE graduate of Georgia Tech an holds MS, CE and PhD degrees from MIT. He taught at MIT for eight years, then spent a ye with INTERA Environmental Consultants before joining the Hydrology Program in Socorro. Dr. Wilson is presently on sabbatical leave at the University of Waterloo in Ontario, Canada.

Dr. Wilson's present-day research interests include the fundamental fluid mechanics of porou media flow and transport, primarily using flow visualization tools. He has other research projects on well-head protection, flow through heterogeneous media, and the geological characterization of aquifers. He has many publications and is Chairman of AGU's Groundwa Committee and is a member of many professional committees and panels.

Fred M. Phillips is Associate Professor of Hydrology at the New Mexico Institute of Mining and Technology He is a BS graduate of the University of California at Santa Cruz an holds MS and PhD degrees from the University of Arizona. He has taught at Socorro for ten years.

Dr. Phillips' research spans a variety of areas, including geological controls on permeability distribution in sediments, radiometric dating of ground water, isotopic tracing of ground water recharge processes in desert soils, reconstruction of fluctuations in the water balance over the Quaternary, and dating of landforms using cosmogenic nuclide accumulation. He was the 19 recipient of the Clarke Medal from the Geochemical Society, awarded for his research on cosmogenic chlorine-36.

Mailing address:

Department of Geoscience
New Mexico Institute of Mining and Technology
Socorro, New Mexico
87801, USA

The role of geology in parameter estimation

John L. Wilson and Fred M. Phillips

Parameter values assigned to simulation models are presumably related to the actual property distributions of real aquifers and reservoirs. These property distributions are themselves a function of the geological depositional environment and subsequent diagenesis Historically this has been recognized by modellers only when dealing with relatively large scale geological features. For example, in hydrology we recognize aquifers and aquitards, and often design our codes around such layered features, as in the popular Modflow code. Reservoir engineers typically subdivide reservoirs into a layercake structure, emulating an easily recognized stratigraphic sequence that is typically simulated using block finite differences. Fractures, if they occur, are assumed to follow the same orthogonal pattern. These standard hydrologic and reservoir conceptualizations are easy to visualize, program, and parameterize. One need only to assign property values to each layer. If desired, various zones may be designated within each layer to provide for any 'necessary' lateral trends in property values. There is little formalism in picking a zoning pattern. one simply tries different and somehow reasonable patterns until 'satisfied'. Yet within each of these layers and arbitrary zones there is additional property variability. As we now recognize, this smaller spatial scale of variation has important influences on pollutant transport in hydrology and the performance of oil recovery efforts in reservoirs. There are many ongoing efforts to incorporate this variability into the models, and to parameterize it.

One approach to this issue employs geostatistical models (e.g. variograms) of the parameter space. These models are used to interpolate sparse and uncertain, but correlated measurements via kriging or co-kriging. The kriged fields and their covariances may in turn be used as prior information in history matching exercises, to provide unique and stable inverse solutions. The parameters of the geostatistical models may themselves be the object of these estimation approaches, but in almost every case the geostatistical model is assumed to be known, or drawn from a small family of possible models. One might ask if the geological world is appropriately described by these geostatistical models?

The real issue is that we typically abandon most of our general and site-specific geological knowledge once we have selected a conceptual model and begin the parameter estimation process, even when using geostatistics. In this paper we explore the use of subjective geological information in the construction and parameterization of appropriate geostatistical models. In particular we investigate the relationship between measurable hydrologic quantities, such as permeability, and observable geological features. If there is a strong correlation between the two, then subjective geological knowledge can be used to dramatically extent the data sets used in parameter estimation.

about the authors...

Timothy D. Scheibe received a BS degree in geological engineering from Washington State University in 1984, and an MS degree in civil engineering from the University of Washington in 1987. He is currently pursuing a PhD in civil engineering at Stanford University, where his research interests are in the area of ground water contaminant transport modelling.

David L. Freyberg is an associate professor of Civil Engineering at Stanford University. After receiving BA and BE degrees from Dartmouth College in 1972, he spent three years in consulting practice in Boston, Massachusetts. In 1977 he received his MS degree from Stanford University. He completed his PhD at Stanford in 1981 and has been on the faculty there since then, where he is responsible for the graduate teaching program in hydrology. His research interests center on contaminant transport in ground water, with a particular emphasis on understanding and modelling the effects of spatial variability and parameter uncertainty in transport prediction and model validation. He is a recipient of a 1985 Presidential Young Investigator Award.

Mailing address:

Department of Civil Engineering
Stanford University
Stanford, California
94305, USA

Understanding the impacts of spatial structuring of natural porous media on the modelling of solute transport in ground water

Timothy D Scheibe and David L. Freyberg

Understanding the relationship between properties of a porous medium at various spatial locations (referred to as 'spatial structure'), and the effect of such structure on flow and transport processes is a key problem in hydrogeology. Knowledge of spatial structure offers one approach to characterization of a porous medium given limited measurements. However, the spatial structure of natural sediments (which exists due to spatial and temporal structuring of depositional processes) is extremely complex, and cannot be completely described. Therefore, models of spatial structure commonly focus on one or more basic characteristics of the structure Examples of such characteristics which have been proposed by various investigators as being of importance to flow and transport prediction include the following: (1) connectedness of extreme values (i.e. existence of high-permeability flow paths); (2) length scales of heterogeneities; (3) second-order ensemble statistics; and (4) geometries of sediment classes.

The current research evaluates the relative impacts of these and other characteristics of spatial structure upon predictions obtained using numerical models of ground water flow and solute transport. The body of observations which has been accumulated by investigators in geological fields of study represents a wealth of information about the types of patterns which occur in natural sediments. We apply this information, along with quantitative measurements, to develop a parameter field, fully characterized at a fine scale, which can be assumed to be a realistic example of a natural sediment. The parameter field is used as input to a solute transport model to obtain the assumed true flow and transport behaviour of the system. The parameter field is then systematically modified, typically using numerical filters, to obtain new parameter fields which de-emphasize specified characteristics of the structure. The results of flow and transport modelling in the modified systems are then compared to those in the original system to delineate those characteristics of the spatial structure which are most important to prediction of solute transport. This information is used to evaluate the applicability of various models of spatial structure to such prediction problems. Models considered include alternative models drawn from the disciplines of pattern recognition and geology as well as models presently in use in hydrogeology.

about the authors...

Lisa D. Shepherd is an MS student in hydrogeology at the University of Wisconsin-Madison She received her BA in geology from Carleton College in 1987. She has experience at the Water Resources Division of the US Geological Survey working on geothermal and subsidence projects.

Jean M. Bahr is an assistant professor in the Department of Geology and Geophysics at the University of Wisconsin-Madison. She has experience in geotechnical consulting and as a hydrologist with the US Geological Survey. Her current research interests include fluid flow and solute transport in shallow and deep systems.

Gerilynn R. Moline is currently pursuing a PhD in hydrogeology at the University of Wisconsin-Madison. She received a BA in geology from the University of Southern Maine in 1986 and an MS in geophysics from the University of Wisconsin-Madison in 1989. Her current research focuses on hydrogeological modelling of deep basin pressure compartments under a grant funded by the Gas Research Institute.

Mailing address:

Department of Geology & Geophysics
University of Wisconsin-Madison
1215 W Dayton
Madison, Wisconsin
53706, USA

Determination of scales of porosity variability through the use of image analysis

Lisa D Shepherd, Jean M. Bahr and Gerily R. Moline

Recent theoretical and field results indicate the importance of heterogeneity in controlling fluid flow and mass transport in porous media. Variability in porosity and permeability can exist over a wide range of scales. The scales of variability in porosity are being investigated for the St. Peter Sandstone in the Michigan Basin. On a macroscopic scale the St. Peter Sandstone is a relatively homogeneous quartz sandstone. However, porosity of the St. Peter can vary from less than 1% to over 20% between core samples obtained from a single well. Abrupt changes in the degree of cementation and porosity can be observed within single thin sections. If these small scale variations in porosity generate areally extensive zones of low effective permeability, they could provide an explanation for the existence of pressure compartments within the St. Peter Sandstone. An image analysis system is being used to quantify porosity variations from thin sections impregnated with blue dyed epoxy. Images of the thin sections are projected onto a computer screen. The user sets an upper and lower sensitivity to pigment to discriminate between porosity and rock matrix. Geostatistical techniques are being used to evaluate vertical and lateral spatial variability and to determine correlation scales. Comparison of these results to core descriptions and wireline log signatures can help to identify patterns of variability on a larger scale. Results of this work are being used to develop a regional hydrodynamic model for the Michigan Basin.

about the authors...

Gerilynn R. Moline is currently pursuing a PhD in hydrogeology at the University of Wisconsin-Madison. She received a BA in geology from the University of Southern Maine in 1986 and an MS in geophysics from the University of Wisconsin-Madison in 1989. Her current research focuses on hydrogeological modelling of deep basin pressure compartments under a grant funded by the Gas Research Institute.

Jean M. Bahr is an assistant professor in the Department of Geology and Geophysics at the University of Wisconsin-Madison. She has experience in geotechnical consulting and as a hydrologist with the US Geological Survey. Her current research interests include fluid flow and solute transport in shallow and deep systems.

Lisa D. Shepherd is an MS student in hydrogeology at the University of Wisconsin-Madison. She received her BA in geology from Carleton College in 1987. She has experience at the Water Resources Division of the US Geological Survey working on geothermal and subsidence projects.

Mailing address:

Department of Geology & Geophysics
University of Wisconsin-Madison
1215 W. Dayton
Madison, Wisconsin
53706, USA

A multivariate statistical analysis of wireline log data for the determination of hydrostratigraphy and hydraulic parameters: St. Peter Sandstone, Michigan Basin

G.R. Moline, J.M. Bahr and L.D. Shepherd

A study is currently underway to investigate the occurrence of pressure compartmentalization in the St. Peter Sandstone of the Michigan Basin. The St. Peter reaches depths exceeding 10,000 ft in much of the basin and is currently an active gas play. A regional flow model is being constructed as part of this investigation. Although more than 500 wells have been drilled to the St. Peter or deeper, only a few cores and permeability analyses have been made available due to the proprietary nature of these data. Thus, for the majority of the basin, the only data available for determination of hydrostratigraphy are wireline logs. A means for correlating these data with lithology and hydraulic parameters is needed. Conventional methods of analyzing well log data utilize two- or three-dimensional cross-plots of log parameters which capitalize on the differences in log response to geologic parameters. While useful for delineating large variations in lithology and porosity, conventional cross-plots are not sufficient to identify the subtle variations observed in the St. Peter Sandstone. An alternative approach being used in this study is a multivariate statistical analysis of the well log data using all available well log parameters. Data points group into regions in n-dimensional space, n being the number of electric log parameters. These regions or "electrofacies" correspond to lithofacies determined from macroscopic and petrographic core description. Permeability and porosity values are assigned to electrofacies by correlation with core analyses and detailed porosity studies currently underway. These correlations provide the basis for quantifying hydrogeological parameters at well locations for which only geophysical data are available.

about the author...

John L. Wilson is Professor of Hydrology and Director of the Hydrology Program at the New Mexico Institute of Mining and Technology in Socorro, New Mexico. He is a BCE graduate of Georgia Tech and holds MS, CE and PhD degrees from MIT. He taught at MIT for eight years, then spent a year with INTERA Environmental Consultants before joining the Hydrology Program in Socorro. Dr. Wilson is presently on sabbatical leave at the University of Waterloo in Ontario, Canada.

Dr. Wilson's present-day research interests include the fundamental fluid mechanics of porous media flow and transport, primarily using flow visualization tools. He has other research projects on well-head protection, flow through heterogeneous media, and the geological characterization of aquifers. He has many publications and is Chairman of AGU's Groundwater Committee and is a member of many professional committees and panels.

Mailing address:

Department of Geoscience
New Mexico Institute of Mining and Technology
Socorro, New Mexico
87801, USA

Visualization of flow and transport in heterogeneous media

John L. Wilson

Spatial variation or heterogeneity of porous media properties influences the flow of fluids, and the transport of colloids and dissolved species. The influence of heterogeneous permeability has been the subject of recent mathematical modelling in hydrology, soil science, and reservoir engineering Less attention has been given to the other properties of the media, e.g. capillarity

We explore the use of flow visualization in etched glass micromodels to help elucidate the influence of heterogeneities on several different flow and transport mechanisms. The micromodels are physical models of a pore space, created by etching a pattern onto two glass plates which are then fused together. The resulting pores have complex three-dimensional cross-sections, although the pore network is only two dimensional. Models of this type have been used to study multiphase flow, miscible displacement, and foam behaviour in petroleum engineering. We have recently applied them to hydrology and pollutant transport issues. The usual focus of a micromodel study is on pore level behaviour, but we have found that bulk properties can also be observed. For example, the pore network can be constructed to emulate an aggregated soil, with well defined preferential flow paths, or an interbedded aquifer or reservoir material, with lenses of a one material buried in a matrix of another material. Observation of behaviour in a micromodel containing many such paths or lenses reveals behaviour that is missing from our mathematical models, and may help to define appropriate equivalent homogeneous or pseudo-properties in those models.

We examine miscible displacement, two and three phase immiscible flow, and colloid transport. The visualizations are recorded on film and videotape. We have found, for example, that media heterogeneities dominate two phase displacement and trapping mechanisms, with implications for aquifer remediation and oil recovery. Non-wetting fluids selectively travel through the coarser and more permeable portions of heterogeneous media, bypassing finer-grained regions. Later, during a natural or imposed flood of a wetting fluid, capillary forces can relegate the flow of the wetting fluid to finer-grained regions, by-passing the coarser non-wetting fluid filled regions. The amount of by-passing depends on the heterogeneity, and a balance of capillary and viscous forces. Following the recovery of non-wetting phase, the residual saturation left behind in, say, a heterogeneous material composed of disconnected coarse lenses, tends to be larger than in a homogeneous material, and depends on the history of the recovery. It is not a constant media property as assumed by conventional mathematical models.

about the authors...

Iraj Ershaghi is a professor and Acting Chairman of Petroleum Engineering at the University of Southern California. His research interests are in the areas of well testing, formation evaluation and reservoir characterization. He has supervised many experimental a analytical graduate studies and research projects.

Dr. Ershaghi received a BS degree in petroleum and mining engineering from the Unive of Teheran in 1965 and MS and PhD degrees in petroleum engineering from the University o Southern California in 1968 and 1972, respectively. He has been with USC since 1972. He also served as a reservoir engineering consultant. He has published numerous papers in area ranging from properties of rocks and fluids at high temperatures to formation evaluation techniques including well testing.

Yusuf A. Shikari is Manager, Storage Research at the Gas Research Institute in Chicag Illinois. He is responsible for the overall planning, procurement and management of gas stor related to research and development programs for the US natural gas industry. He is also responsible for providing analytical and strategic support to GRI's executive management in overall budgeting of its transport and storage research. Prior to working with GRI, Mr. Shik was Research Business Analyst at IIT Research Institute. He holds BS and MS degrees in mechanical engineering and an MBA in finance and statistics.

Huseyin Calisgan is a graduate student at the University of Southern California. He received his BSc degree from the Middle East Technical University in Ankara in 1987. His research interests are in well testing and numerical modelling of thermal recovery processes.

Mailing addresses:

I. Ershaghi and Huseyin Calisgan
Department of Petroleum Engineering
University of Southern California
University Park - Hedco 316
Los Angeles, California
90089-1211, USA

Yusuf A. Shikari
Gas Research Institute
8600 West Bryn Mawr Avenue
Chicago, Illinois
60631, USA

Estimation of reservoir parameters in heterogeneous gas storage reservoirs under aquifer support

I Ershaghi, H. Calisgan and Y. Shikari

This paper reviews the significant differences between a gas reservoir and a gas storage reservoir as related to estimation of reserves, average reservoir pressure and deliverability forecasting. Specifically, the effect of cyclical movement of gas/water interface in the reservoir for storage system is examined. Additionally, the interference among wells during simultaneously conducted buildup and fall-off tests affects the response from individual wells and parameters may be erroneously estimated using conventional diagnostic pressure derivative plots.

Common practice of using wellhead recorded spot pressures under the conditions described above is conducive to uncertainties in estimating of required duration of a test period. Additionally, heterogeneities in reservoir properties affects the test duration under the influence of other wells.

Application of a new method using a composite plot of individual well responses for a hypothetical equivalent well located at the center of gravity for the reservoir is illustrated. We have developed an analytical formulation of a well in gas storage reservoirs containing several interfaces; i.e., gas-gas transition, water transition and aquifer. Our study shows that deliverability tests conducted under a certain reservoir position of interfaces may not be applicable to future forecasting where the interfaces may have changed because of over- or under-pressurization of the storage reservoir.

about the authors...

Sait Kocberber is a senior engineer with Research and Engineering Consultants, Inc He received his BS in petroleum engineering from Middle East Technical University, Turkey, his MS in petroleum engineering from Stanford University and his PhD in petroleum engineering from the University of Texas. Sait came to the United States on Turkish government scholarships and specialized in simulation and simulator development while at university He is now involved in developing simulation techniques for heterogeneous reservoirs, specifically oil recovery from cross-bedded systems.

R.E. (Gene) Collins is a physicist and mathemancian by training, a petroleum engineer, biophysicist and hydrologist by avocation, and a registered profesional engineer in Texas. He received his BS degree from the University of Houston, his MS and PhD from the Texas A&M University, all in physics. He has forty years experience, in research positions with Exxon, Mobil, Amoco and the Texas Petroleum Research Committee, academic appointments as professor of physics and biophysics at the University of Houston, the W.A. "Monty" Moncrief Chair in Petroleum Engineering at the University of Texas at Austin, and the Champlin Professorship in Petroleum Engineering at Montana Tech. He has consulted for many large companies and government agencies over the years and has published over 100 technical articles and books including the classic text "Flow of Fluids Through Porous Materials", first published in 1961 and later translated into Russian and Japanese. He also authored the graduate level text "Mathematical Methods for Physicists and Engineers" published in 1968 and most recently, "Characterization of Heterogeneous Reservoirs", published in 1985.

Mailing address:

Research and Engineering Consultants
5445 DTC Parkway #640
Englewood, Colorado
80111, USA

The impact of large scale heterogeneities on hydrocarbon recoveries

Sait Kocberber and R Eugene Collins

The effects of large scale heterogeneities on multi-phase flow have been addressed only on a limited scale in previous studies In this study, a fundamental method for incorporating large scale heterogeneities into reservoir studies in a general way is presented. This is achieved by utilizing a three-dimensional, three-phase, black oil model using representations for relative permeabilities and capillary pressures conditioned by absolute permeabilities and employing initial distributions of fluid saturations based on gravity-capillary equilibrium.

First, a small scale model is used to evaluate recovery by solution-gas drive in a three-dimensional, rectangular block containing two or three cross-bed laminae with an initial fluid distribution based on capillary-gravity equilibrium. The block is depleted by fluid withdrawal at a face while the other faces of the block are sealed. These results are employed to extend the model to simulate field sized recovery processes in systems having large scale heterogeneities. These results indicate that the recovery history is strongly dependent on the configuration of heterogeneities and the direction of flow. Capillary effects cause high water saturation buildup in tight laminae. Because of their low relative permeability, these laminae act as flow barriers to hydrocarbon flow causing very non-uniform recovery patterns.

Results of these studies indicate that many common practices in previous simulation studies are not representative of real reservoir behaviour.

about the author...

Valery A. Mironenko was born in Leningrad, graduated from the Leningrad Mining Institute as a specialist in hydrogeology and engineering geology, and subsequently from the Leningrad State University with a specialization in mathematics and mechanics. Since 1969 he has been a professor at the Leningrad Mining Institute in the Department of Hydrogeology. The main direction of scientific activities include. ground water hydraulics. mining hydrogeology and engineering geology, hydrogeological tests and observations, and modelling of the hydrogeological processes. Dr. Mironenko is a UN expert on water resources and a member of the American Insutute of Hydrology.

Mailing address:

Mining Insotute
Tverskaja 18
Leningrad 193124, USSR

Assessment of the rational set of field tests in heterogeneous aquifers using simulation models

V.A. Mironenko

The theory and practice of aquifer tests involve a number of unsolved problems, among being: (1) evaluation of the quality of estimated parameter values in view of their use in subsequent forecasts; (2) quantitative comparison of the quality of different kinds of test resu (3) justification of the expedient number of aquifer tests and their distribution by types and operation stages within the area under investigation. Simulation modelling provides new possibilities for studying these problems. It helps to study a complex system with uncertain structure on the basis of multivariate experiments with an adaptive constructed model in the course of which the probabilistic structure of the system, its possible behaviour and optimal functioning conditions are found.

In our case, 'the aquifer - the set of field tests - the engineering structure (water intake, drainage, etc.)' system is studied in this way. Simulation experiments, using a numerical flo model, are planned and made by two independent groups of experts. One of them represents (invents) the input data about the aquifer system and simulates its 'true' behaviour in the cou of its exploration and exploitation, while another group plans field tests and interprets their results, designs an engineering structure and predicts its behaviour, i.e. simulates hydrogeologists' work under conditions of uncertainty. The comparison of the estimated effe of field tests and aquifer's exploitation (numerical experiments of the second group) with the 'true' effects (first group's results) gives an idea of the quality of field test results and forecas estimates made on their basis, depending on the types, quantity, and locations of field tests.

These studies have been carried out for a number of typical simulated objects with differ characteristics of spatial variability of aquifer properties and with simulation of typical test shortcomings. The experiments resulted in obtaining the relations between the cumulative en of tests and their number, as well as pertinent relations for the forecast error. The resulting measure of the test quality is the relation between the number of tests and total expenses whic include the test costs and the risk of economic losses in the course of water-intake operation d to lack and errors of information about flow parameters.

The practical conclusions concern the evaluation of regional parameters from a totality o local tests results, the relative reliability and informativeness of different types of tests in heterogeneous aquifers, and the expedient amount of various tests. The overall conclusion co of the necessity of the appreciable rise in the quantity of relatively large-scale and expensive multi-well tests as well as the expenses of hydrogeological surveys as compared to currently adopted empirical standards

Thursday, September 20, 1990

about the author...

Peter Kitanidis is a hydrologist whose main area of expertise is the use of measurements and mathematical models in estimation with incomplete information. He has worked extensively on the problem of calibration and validation of ground water models. Much of his recent work deals with the determination of models and parameters which describe flow and transport at the field-scale in highly heterogeneous formations; and the development of macroscopic transport models from the study of transport at the pore scale. He has also contributed to the literature on hydrologic forecasting, the optimization of sampling and control strategies, dynamic programming, and river mechanics.

Mailing address:

Department of Civil Engineering
Stanford University
Stanford, California
94305-4020, USA

A conceptual framework for the geostatistical approach to the inverse problem

Peter K. Kitanidis

This paper presents an overview of the geostatistical approach to the inverse problem with emphasis on the conceptual basis of the methodology. In particular, the problem is presented as one of prediction with incomplete information rather than a classical statistics or frequency analysis problem. The principles of maximum entropy and Bayes' inference are explained and it is shown that, under certain assumptions, they lead to the geostatistical approach. This interpretation sheds light on the meaning of the probabilistic model and the error bounds on the predictions; the strengths and limitations of the normality assumption; and the relevance of maximum likelihood estimation. Furthermore, the insight leads to new algorithms appropriate for, among others, large-variance problems.

about the author...

Bryan Travis has a BA in mathematics and physics and a doctorate in applied mathematics. He has worked at Los Alamos National Laboratory since 1974 on a variety of porous flow problems, concentrating on numerical simulation of multiphase flow and transport, use of moving finite element methods for parabolic equation systems (e.g., porous flow and magnetotellurics), and optimization problems, including methods for solving inverse problems. Applications have ranged from in situ recovery of hydrocarbons from shale deposits, to geological storage of radioactive waste, to remediation methods for organic hazardous waste site.

Mailing address:

Earth and Environmental Sciences Division
Los Alamos National Laboratory MS-F665
Los Alamos, New Mexico
87545, USA

Recovery of discontinuities using a parametric form of regularized inversion

Bryan J. Travis

Inverse problems are usually ill-posed a priori because of lack of uniqueness and stability. This difficulty can frequently be overcome by making additional assumptions, the most important of which is to apply Ooam's razor, i.e. find the simplest solution possible that fits the data. This is generally interpreted to be the smoothest solution in some sense. Computationally, this can be achieved by searching for the solution with the smoothest derivative of some order (usually first or second derivative or a combination thereof).

The regularization method of Tikhonov is a popular technique for solving inverse problems by derivative smoothing. The method was originally applied to integral equations, but via Lagrange multipliers (the adjoint solution), it can be used for systems controlled by differential equations (ordinary and partial), and in multiple dimensions. Other constraints, such as positivity can be imposed to improve resolution.

Regularization smooths out unwarranted structure. However, in many cases, the structure sought (for geological layering, for example) is not smooth everywhere, but may have discontinuities at some locations. These abrupt changes can be recovered within the regularization methodology by recasting the procedure in a more general, parametric form. One-dimensional and two-dimensional examples are given to illustrate this approach for resolving spatial permeability distributions in reservoirs.

about the authors...

Jianian Xiang earned his Master of Engineering degree from the Graduate School of the Institute of Water Conservation and Hydroelectric Power Research (IWHR), China. After working at IWHR and the Mathematical Modeling Department of ISMES in Italy, he obtained his Master of Science degree at Penn State University. He is currently working on his PhD in the general area of computational mechanics.

Derek Elsworth is currently Assistant Professor in the Department of Mineral Engineering at Penn State following faculty positions at the Universities of Toronto and Waterloo in Canada. His research interests center on flow and transport of fluids in deformable porous and fractured geological media.

Mailing address:

Department of Mineral Engineering
Pennsylvania State University
104 Mineral Sciences Building
University Park, Pennsylvania
16802, USA

A comparison of several optimization methods for inverse solution of ground water flow systems

Jiannan Xiang and Derek Elsworth

Inverse solution may be effectively used to determine in situ hydraulic parameters at field scale. Where data is limited to m spatially distributed values of transmissivity and n distributed hydraulic head magnitudes, the distribution of transmissivity in the remainder of the domain may be determined from any suitable inverse method. Indirect methods are widely used in this class of problem because of their flexibility and ability to handle nonlinear parameters and constraints. However, the effectiveness of these methods varies considerably with the adopted optimization technique. A comparison is completed between six well-known optimization methods in the minimization of a multidimensional functional. The relative performance of these methods are compared using one dimensional and two dimensional examples. The differential equation of flow is represented by a low order finite element that has been shown to perform well. Five cases are studied under different levels of data completeness or incompleteness. Results indicate that all methods perform well for complete data but may be ranked according to solution time. Under incomplete data, computational requirements are increased with the Quasi-Newton method yielding the most accurate results. The Levenberg-Marquardt method performs with high accuracy and exhibits rapid convergence although the CPU requirements are greater than the Gauss-Newton method. Where different initial estimates are used to start the iteration, unique transmissivity distributions result for cases of complete data. Under incomplete data the results are non-unique.

about the author...

Robert William Ritzi, Jr. is a faculty member in the Department of Geological Sciences, Wright University. He received his PhD in 1989 from the Department of Hydrology and Water Resources at the University of Arizona. He has MS and BA degrees in geological sciences from Wright State University and Wittenberg University respectively.

Mailing address:

Department of Geological Sciences
Wright State University
Dayton, Ohio
45435, USA

Inverse modelling in the frequency domain: the example of estimating hydraulic conductivity from observations of the combined solid earth tide and atmospheric pressure influence

Robert William Ritzi, Jr.

Parameter estimation schemes which include frequency domain models for ground water flow and mass transport have traditionally been posed with estimation criteria based upon modulus or phase transformations of the model frequency response function (FRF) and the sample FRF. A better approach is to use an estimator with a complex vector estimation criterion because it has less bias and variance, and is more robust. This is demonstrated in considering the estimation of hydraulic conductivity from well response to the combined Earth tide and atmospheric pressure influence.

Regardless of which criterion is used, hydraulic conductivity is only identifiable if the data are sufficiently informative. An estimation scheme using the combined solid Earth tide and atmospheric pressure information (CSA), when compared to schemes using only the individual Earth tide or atmospheric pressure information, will give the greatest probability that sufficient information is contained in a data record so that K is indeed identifiable. The CSA scheme also gives estimates with the greatest precision, and requires the shortest length of time series data.

about the authors...

P.R. McGillivray received his BSc in geophysics from the University of British Columbia in 1984. He has been employed as an exploration geophysicist by Canadian Superior Oil Ltd. and Mobil Oil Canada Ltd. He is presently a PhD candidate with the University of British Columbia. His current research interests include the solution of large scale modelling problems using adaptive multigrid techniques and the solution of inverse problems in ground water and geophysics.

D.W. Oldenburg received a BSc (honours) in physics in 1967 and an MSc in earth science in 1969, both from the University of Alberta and a PhD in earth sciences in 1974 from Scripps Institute of Oceanography. He was a Killam Postdoctoral Fellow at the University of Alberta from 1974 to 1976. Since 1977 he has been with the Department of Geophysics and Astronomy at the University of British Columbia where he is currently a professor. His interests centre around the application of inverse theory to problems in electromagnetic and seismic data processing. He is a member of SEG, EAEG and the CSEG.

Mailing address:

Department of Geophysics and Astronomy
University of British Columbia
2219 Main Mall
Vancouver, British Columbia
V6T 1W5, Canada

The inversion of pole-pole resistivity data in the solution of ground water contamination and enhanced oil recovery problems

P.R. McGillivray and D.W. Oldenburg

The pole-pole resistivity experiment is a geophysical technique which has been used primarily in mining and geothermal exploration. The experiment involves injecting current into the ground and then measuring the resulting voltages using a grid of electrodes set up over a survey area. Each electrode in the grid can serve as either a voltage or current electrode, and consequently a high density of data over the area of interest is recorded. An interpretation of this data set based on forward modelling and inversion can then be used to delineate regions of anomalously high or low electrical conductivity at depth. Because electrical conductivity can be related to properties of the aquifer and the distribution of fluids within the aquifer, the technique could be applied to a wide variety of problems in both ground water and petroleum reservoir evaluation. The goal of this paper is to describe a method for recovering the conductivity distribution of the subsurface from pole-pole voltage measurements using a non-linear parametric inverse approach. The importance of selecting the appropriate global norm to minimize and the use of a priori information to help resolve non-uniqueness in the solution will be emphasized. The use of voltage data from cross-borehole measurements to further constrain the inversion will also be discussed Finally, the inversion of synthetic data sets over a contaminant plume and an enhanced oil recovery site will be used to illustrate applications of the technique.

about the authors...

Malcolm Reeves has been involved in ground water modelling since 1970. In the United Kingdom, between 1970 and 1976 he worked at the Water Resources Board, Water Research Center and the Central Water Planning Unit of the Department of the Environment. Before coming to Canada in 1982 he was a lecturer in engineering geology at the University of Durham in England. Dr. Reeves is a professional engineer and is a full professor in geological engineering in the Department of Geological Sciences at the University of Saskatchewan. He also holds an associate appointment in the Department of Civil Engineering.

Rebecca Yost Grambo graduated from South Dakota School of Mines in 1985 with a BA in geological engineering. She is currently enrolled in a PhD program in the Department of Geological Sciences at the University of Saskatchewan. Her thesis topic is a regional model study of the Regina aquifer system. Mrs. Grambo is a member of the Association of Engineering Geologists and has gained practical experience of hydrogeology from summer jobs in southern California.

Mailing address.

Department of Geological Sciences
University of Saskatchewan
Saskatoon, Saskatchewan
S7N 0W0, Canada

Modelling a multi-unit aquifer system with uncertainty in both aquifer properties and aquifer geometry

Malcolm Reeves and Rebecca Yost Grambo

In recent years it has become common practice to employ Monte Carlo techniques in stochastic simulations to take account of uncertainty in aquifer modelling. Geostatistical methods have been applied to estimate the spatial distribution of many parameters including aquifer characteristics, thicknesses and piezometric surfaces. These methods are particularly useful in allowing for variance reductions associated with scale when point data are used to predict values for large "blocks" in numerical models.

Here we describe a methodology for treating uncertainty in both aquifer properties and aquifer geometry for a multi-unit, glacial, sand and gravel, aquifer-complex. The procedure uses interpreted well logs together with more subjective geological and geomorphological models of the morphology of glacial sediments, to constrain sets of bounding surfaces for permeable sand and gravel bodies within a relatively impermeable clay-till matrix. For each set of surfaces, analysis of "overlap" is used to assign vertical conductances to a multi-layer numerical model. Horizontal hydraulic conductivities and storage coefficients are estimated using a geostatistical model for spatial variability.

Numerical models are run for a standard sequence of infiltration conditions to generate hydrologic budgets for the various sub-units within the aquifer-complex. The ultimate objective of the research is to establish probability functions for inter-aquifer flows and the associated covariance structure.

The case-study area is centered on the city of Regina, Saskatchewan. Only approximately 900 wells, many quite shallow, were available to characterize an area of some 29,000 km^2 where significant sand and gravel bodies are found at four distinct stratigraphic horizons. Post-depositional erosion and solution collapse features have resulted in the potential for interconnection between permeable units. The degree of interconnection between the various aquifers has major implications for the assessment of the risk of ground water contamination.

about the authors...

James C. Redwine is a senior hydrogeologist/engineering geologist and is presently working with the Earth Science and Technology Department of Southern Company Services. Mr. Redwine's responsibilities range from project development to ground water investigations to geological resource evaluations. The subject matter of this presentation is part of his dissertation research performed in partial fulfillment of requirements for his PhD in geology at the Department of Geosciences, Pennsylvania State University.

Fred J. Molz received his BS degree in physics and MS degree in civil engineering from Drexel University. He received his PhD in hydrology in 1970 from Stanford University and shortly after joined the Civil Engineering Department at Auburn University. He has served as Director of the Engineering Experiment Station and Assistant Dean for Research in the College of Engineering. In 1984, Dr. Molz was awarded the Feagin Professorship in Civil Engineering and in 1990 was appointed by Auburn University to the Huff Eminent Scholar Chair. His research interests include both the practical and theoretical aspects of water and pollutant transport in the ground water/soil/plant/atmosphere system; he has authored/coauthored approximately 100 publications. Dr. Molz holds membership in the American Geophysical Union, National Water Well Association, American Society of Agronomy and the Soil Science Society of America.

Mailing addresses:

James C. Redwine
c/o Southern Company Services Inc.
PO Box 2625
Birmingham, Alabama
35202, USA

Richard R. Parizek
Pennsylvania State University
University Park, Pennsylvania
16802, USA

Fred J. Molz
Department of Civil Engineering
Harbert Engineering Center
Auburn University
Auburn, Alabama
36849-3501, USA

Controls on porosity and permeability in fracture-flow/conduit-flow rocks of the Knox Group, Southern Appalachian Fold-and-Thrust Belt, USA

James C. Redwine, Richard R. Parizek and Fred J. Molz

Alabama Power Company's Logan Martin reservoir is located on folded, faulted, fractured and solutioned rocks of the Cambro-Ordovician Knox Group in east-central Alabama, USA. The reservoir loses significant quantities of water through the underlying fracture-flow/conduit-flow aquifer system, which diminishes hydroelectric power generation at the site. For this and other reasons, subsurface investigations have been ongoing at the Logan Martin site for the past 30 years. Major categories of information include studies of aerial photography and remotely-sensed imagery; approximately 265,000 piezometer readings; dye and tracer test data; surface and subsurface geological mapping and modelling; temperature information; water chemistry data; surface and downhole geophysics; packer (hydraulic conductivity) testing; grouting records; and sinkhole mapping. Recently, this information has been pulled together to identify and estimate flow and transport parameters, particularly controls on porosity, permeability, and discrete flow paths. Major geological controls include the upper Knox/lower Knox contact; various rock types; fold structures; regional and local thrust faults; local normal faults; regional cross-structural discontinuities; fracture systems of various ages; near-vertical zones of fracture concentrations; present karst and paleokarst horizons; mappable features of unknown origin; and combinations and interactions of the various controls. Work is presently underway to detect discrete flow paths with borehole flowmeters using both state-of-the-art and prototype equipment. This quantitative hydraulic testing, when combined with the previous hydrogeological work, will be used to develop a methodology or procedure for quantifying flow and physical transport parameters in complex geological terrain. The investigators can develop a hierarchy of controls, and because of the extensive site investigations, determine the most cost-effective methods for parameter identification and assessment. This work applies not only to ground water problems in fracture-flow and conduit-flow aquifers, but also to oil and gas exploration and development in such rocks.

about the author...

Larry Lake is chairman of the Department of Petroleum Engineering at the University of Texas at Austin and director of the Enhanced Oil Recovery Research program. His research areas are enhanced oil recovery, reservoir characterization and in situ leaching Dr. Lake has been teaching for 12 years prior to which he worked for Shell Development Company in Houston, Texas.

Dr. Lake holds BSE and PhD degrees in chemical engineering from Arizona State University and Rice University. He has authored or coauthored more than 70 technical articles, 12 major reports, 2 conference proceedings and 1 textbook. In addition, Dr. Lake has conducted numerous industrial and professional society short courses in enhanced oil recovery and reservoir characterization. Since 1988 Dr. Lake has held the Shell Distinguished Chair in petroleum engineering.

Mailing address:

Department of Petroleum Engineering
University of Texas at Austin
Austin, Texas
78712, USA

Simulating fluid flow through a geologically realistic permeable medium

Larry W. Lake

For the past five years we have been studying the Page Sandstone outcrop in northern Arizona as a prototype for eolian oil reservoirs and aquifers. The work has encompassed detailed geological studies and highly intensive descriptions of the distribution of hydraulic conductivity or permeability. We are now at the point of using this information to evaluate predictions about fluid flow through naturally-occurring sands. Work on this topic is the subject of this presentation.

The first step in the study was to establish a "truth case", a standard against which to measure the success of alternative procedures for flow prediction. Our truth case consisted of a highly detailed (more than 11,000 finite element nodes) numerical simulation of a miscible displacement through a portion of the outcrop wherein each nodal property was assigned according to the actual value existing at that point. This intensely deterministic simulation also allows us to evaluate the extent of geological detail necessary for a good prediction; mobility ratio and the distribution of average permeability are the most important quantities governing fluid flow. Permeability anisotropy, fourth order bounding surfaces and dispersion are much less important.

With the truth case in hand, we redo the simulations based on the amount of data that would normally be available for subsurface conditions. In this case, of course, it is the generation of interwell properties which is being tested. The work investigates two basic procedures: pseudofunctions and conditional simulation. The pseudofunction approach generates effective relative permeabilities (a concept borrowed from immiscible flow) to model the effects of heterogeneities on a gross or flow unit scale. The effective relative permeabilities now depend on the size of the flow units, the mobility ratio and the nature of the distribution of the permeability within the flow unit. The conditional simulation approach generates interwell properties statistically and evaluates each procedure according to whether the distribution of the simulation results agree with the results of the truth case.

Pseudofunctions rely almost exclusively on geological information and conditional simulation on statistics. We should be able to infer the merits and drawbacks of both methods from this work.

about the authors...

Elliot N. Yearsley is a geological engineer and log analyst for COLOG, Inc., Golden. He received his BS in geological engineering from the Colorado School of Mines in 1981, and his MS in engineering mechanics in 1989. Between earning these degrees, Elliot was employed as a geological engineer for Tenneco Oil Company where he pioneered the use of Measurement While Drilling (MWD) formation evaluation. With COLOG he is currently working on new borehole geophysical techniques applied to geochemical and hydrogeological investigations, including monitoring well completion evaluation and full waveform acoustic analysis applied to permeability determinations.

Robert E. Crowder is President of COLOG, Inc. in Golden and has twelve years diversified experience in borehole geophysical applications, including environmental, geotechnical and mineral investigations. Prior to forming COLOG he was Operations Manager for Colorado Well Logging for eight years. He has taught numerous courses for client groups in borehole geophysical logging and log interpretation, both domestic and international. He received his degree in engineering geophysics from the Colorado School of Mines in 1978.

Mailing address:

COLOG, Inc.
1019 - 8th Street, Suite 100
Golden, Colorado
80401, USA

Review of state-of-the-art borehole geophysics applied to hydrogeology

E.N. Yearsley and R.E. Crowder

The application of borehole geophysics to hydrogeological problems is rapidly expanding, driven by the increased need for better in situ aquifer characterization. A number of borehole geophysical technologies have recently emerged that are specifically developed to meet this need. This paper reviews those technologies, which include equipment and data processing capabilities that are new to the ground water industry, as well as existing borehole methods that have become particularly relevant in hydrogeological investigations.

These borehole geophysical applications are divided into three categories: (1) fracture characterization; (2) methods in characterizing permeability profiles, and (3) vadose zone moisture monitoring. Field examples demonstrate these applications, and briefly review their operational features. The field examples involve the acquisition and processing of full waveform acoustic logs, flow meter methods, borehole televiewer, induction logging, and neutron moisture monitoring.

Most attention in this paper is given to those technologies which are commercially available or within the capability of engineering and environmental contractors to perform. Needs for further development and limitations of these technologies are also addressed.

about the author...

Bruce Manchon is a project hydrogeologist with International Technology Corporation, and has more than twelve years experience in the environmental and petroleum fields. The past three years have been devoted to hazardous waste site assessments and remediation. Relevant work experience to the subject matter includes detailed borehole geophysical log interpretation, computer modelling, contaminant transport, aquifer contamination detection, well construction and design, subsurface mapping and stratigraphic analysis. He is a Registered Geologist in California, Arkansas and Delaware.

Mailing address:

International Technology Corporation
4585 Pacheco Boulevard
Martinez, California
94553, USA

Aquifer parameters defined by borehole geophysics

Bruce Manchon

Ground water contaminated with waste migrating from a landfill, surface spill or leaking underground storage tank (UST), or by injection will create distinctive borehole geophysical log signatures. The distinctive contaminated signatures on the logs and log responses of the native conditions from upgradient wells provide hydrogeological parameters of the aquifer and associated contaminate plume. Interpretation of the log responses by borehole geophysical interpretation techniques will identify aquifer and contaminant characteristics.

Borehole geophysics is primarily used in the environmental field to determine lithology, not to delineate the nature of fluids in a formation. Borehole geophysical interpretation provides a means of determining not only the lithology, but the nature of the fluids in an aquifer.

Borehole geophysical interpretation techniques apply in a variety of environmental settings. They are especially effective in terrains where stratigraphy is locally continuous and there is a resistivity or radioactive contrast between the formation water and the contaminants. It can provide data about a contaminant plume's dimensions and concentrations or verify model plume predictions.

This paper will explain, by use of geophysical logs and interpretation techniques, how to identify and estimate parameters of the lithology and fluids of an aquifer.

about the author...

Rainer K. Senger is a research associate with the Bureau of Economic Geology, The University of Texas at Austin. He received an MA in geology in 1983 and a PhD in geology in 1989, both from the University of Texas at Austin. His research interests include applications of numerical models for simulating fluid flow in aquifers and hydrocarbon reservoirs, evaluation of aquifer and reservoir properties, hydrogeological characterization of carbonate aquifers, and development of well-head protection strategies in confined aquifers.

Mailing address:

Bureau of Economic Geology
The University of Texas at Austin
Box X
Austin, Texas
78713-7508, USA

Regional characterization of variable-density fluid flow in sedimentary basins: implications on modelling strategy

Rainer K. Senger

Characterization of regional ground water flow in sedimentary basins requires estimates of regional-scale hydraulic properties that are difficult to determine. Alternatively, permeabilities may be calibrated in regional flow models on the basis of fluid pressure and/or hydraulic head measurements. Fluid-pressure distribution in mature sedimentary basins is typically controlled by steady-state flow driven by potential energy represented by the shallow water table, which generally follows the topography. However, in saline aquifers fluid pressures are significantly affected by fluid densities; furthermore, pressure or head gradients may not reflect actual ground water flow patterns in cases where buoyancy forces associated with high fluid densities dominate the topographically driven flow component. In addition to the well known problems of hydraulic parameter and boundary condition uncertainties, modelling strategies for regional, variable-density ground water flow require consideration of uncertainties associated with fluid densities and evaluation of fluid pressures or equivalent fresh water heads.

Effects of significant fluid-density variation on regional ground water flow are studied in the Palo Duro Basin, Texas, where fluid densities vary between 1.0 and 1.15 g/cm^3. Steady-state flow of variable-density ground water is simulated based on computation of equivalent fresh water heads and stream functions, incorporating fluid densities that vary in space but are time invariant. Simulated equivalent fresh water heads in the variable-density model significantly increase with depth in comparison with simulated heads assuming uniform fresh water density. Constructed surfaces of equivalent fresh water heads in saline aquifers may exhibit large local variations due to vertical offset between test intervals in adjacent wells. Permeability variations and boundary conditions in the variable-density model have much smaller effects on simulated heads than in the constant-density model, which is important for model calibration. However, the overall ground water flow pattern in the Palo Duro Basin is not significantly affected by variations in fluid densities, indicating that the flow component arising from the present-day topography dominates buoyancy forces associated with dense fluids.

about the authors...

Emanuel Mazor holds the F.W. Considine Professorial Chair in Hydrological Research. He was born in 1933 and has lived in Israel since 1936. He is currently a professor at the Weizmann Institute of Science and his research interests include terrestrial noble gases, ground water hydrology and geology of the Ramon National Geologic Park.

Adi Bosch was born in 1960 and is currently a PhD student with the Geoisotope Group of the Weizmann Institute of Science. His MSc thesis topic was "Natural gas association with water and oil, and relative ages, as depicted by noble gases". His current research interests include noble gases in crustal fluids.

Mailing address:

Geoisotope Group
Weizmann Institute of Science
Rehovot 76100, Israel

Boundary conditions for modelling of ground water and petroleum systems: noble gas contributions

Emanuel Mazor and Adi Bosch

Atmospheric Ne, Ar, Kr and Xe and radiogenic He and Ar provide means to formulate boundary conditions necessary for the construction of hydrological conceptual models of large ground water and petroleum systems. Examples include: (1) recharge temperatures (deduced from atmospheric noble gas (ANG) concentrations); (2) porous vs conduit controlled flow in the aerated zone (interpretation of ANG-derived recharge temperatures), (3) identification of karstic flow (excess air and rainy season ANG temperatures); (4) depth of ground water circulation (comparison of ANG recharge temperatures with emergence temperatures); (5) identification of underground dissolution brines and residual evaporation brines (ANG contents as in air-saturated fresh water vs lower ANG concentrations); (6) check of hydraulic interconnections and suggested flow directions (distribution of He concentrations); (7) identification of gas caps (ANG in produced fluids in excess over the concentrations in air-saturated water (ASW)); (8) losses and gains of volatiles and reconstruction of initial gas concentrations (comparison of measured ANG concentrations with those in ASW); (9) He and Ar dating of underground fluids; (10) establishing the degree of drainage of confined systems (comparison of He and Ar derived ages with hydraulic age); (11) identification of mixing of old and young waters; (comparison of He and Ar derived ages with ages derived by other techniques); (12) identification of water-gas and water-oil associations (comparison of ANG patterns with those predicted from solubility data); and (13) He and Ar dating of the hydrocarbons.

about the authors...

Emanuel Mazor holds the F W. Considine Professorial Chair in Hydrological Research. He was born in 1933 and has lived in Israel ce 1936. He is currently a professor at the Weizmann Institute of Science and his research interests include terrestrial noble gases, ground water hydrology and geology of the Ramon National Geologic Park.

Levy Kroitoru is a principal geoscientist with Battelle. He received his MSc in hydrogeology from Tel Aviv University in 1980 and a PhD in geochemistry in 1987 from the Weizmann Institute of Science. He has worked for Battelle in the Office of Nuclear Waste Isolation as a Project Manager and for TAHAL Water Planning for Israel. His research interests include ground water investigation and resource evaluation by physical, chemical and isotopic methods.

Mailing addresses:

Emanuel Mazor
Geoisotope Group
The Weizmann Institute of Science
Rehovot 76100, Israel

Levy Kroitoru
Battelle
OWTD
7000 South Adams Street
Willowbrook, Illinois
60521, USA

Boundary conditions needed for ground water modelling, derived from isotopic, chemical and physical measurements: Mediterranean-Dead Sea transect

Emanuel Mazor and Levy Kroitoru

Hydrological physical, chemical and isotopic measurements serve to define boundary conditions, to be accounted for in the construction of detailed hydrological conceptual models. Models derived in this mode pave the way for mathematical modelling with a minimum of unknown parameters, that otherwise have to be assumed. The methodology is demonstrated on a hydrological transect from the Mediterranean Coastal Plain, through the Judean Mountains to the Rift Valley.

The boundary conditions reached from the various measured parameters indicate that the recharge at the Judean Mountains is rapid and karstic. The western drainage of the system toward the Coastal Plain has an upper slow flow system and a deeper fast-karstic flow system. The eastern drainage toward the Rift Valley has a flow path that is a reverse picture of the western drainage, an upper fast-karstic flow system emerging in the Judean Desert springs and a deeper slow flow system encountered by deep water supply wells.

about the author...

Joe O. Davis is an independent consultant offering specialized services for environmental projects, hydrogeological applications, and engineering design. Since graduating with a BSc in geophysics from the University of Calgary in 1987, Joe has been actively involved in performing and interpreting all types of electrical and shallow seismic surveys. His project scope includes contamination tracing and monitoring, water exploration, engineering projects, and gold, silver and base metal exploration.

Mr. Davis is a member of the International Association of Hydrogeologists, the National Water Well Association, the Vancouver Geotechnical Society, the BC Geophysical Society and is a member in training with APEGGA.

Mailing address:

Omega Geophysics Ltd.
203 - 888 Burrard Street
Vancouver, British Columbia
V6Z 1X9, Canada

Remote sensing of contamination using geophysical electromagnetic methods

Joe O. Davis

The use of geophysics in the petroleum and mining industries is common, its use is increasing in geotechnical, hydrogeological and contamination projects. The major advantage of the inclusion of geophysical methods in projects is lowered drilling costs; yet in many cases information acquired from geophysical methods is prohibitively expensive to obtain by other means.

The use of electromagnetic data for remote sensing of contamination is an innovative technique which relies on the electrical resistance change caused by the introduction of a contaminant into ground water. The technique requires that the contaminant appreciably alter the resistance of ground water beyond the background level changes due to varying lithology or fill materials. The level of contaminant required to achieve this threshold level can be calculated for specific sites and can be substantially lowered by rejecting resistance changes caused by near surface fill materials, or clays. Considering these factors, it is especially important that the contaminant specialist consultant be a geophysicist experienced in contamination projects, and he or she is contacted preferably during planning stages.

Electromagnetics is used to highlight contaminated areas initially. This information is used to locate drill holes in the areas of highest contamination, saving a substantial number of test holes. By correlating electromagnetics to drilling data, gross volumes of contaminants can be calculated, and their thicknesses mapped in plan view. This paper outlines these techniques and provides field examples.

about the author...

Dr. Ballukraya has a Master's degree in geology and a Doctorate in ground water geophysics. He has over fifteen years of professional experience in the field of hard rock hydrogeology, having worked as a consultant during 1971-1986, carrying out assignments in geophysical exploration, ground water assessment, well site location, design and construction of borewells. He joined the Department of Applied Geology, University of Madras in 1986 where he is presently teaching. His research interests are mainly in the field of hard rock aquifers.

Mailing address:

Department of Applied Geology
University of Madras
Guindy Campus
Madras 600 025, India

Geoelectrical parameters in hard rock hydrogeology

P N Ballukraya

Hydrogeology of hard rock aquifers is quite complex controlled as they are by such diverse factors as degree and extent of weathering, fracturing and jointing and recharge availability. The fractures below the weathered rock zone are the main producing zones in the crystalline complex of southern India. A study of several hundred borewell logs indicate that generally the yield of a borewell does not depend on either the degree of weathering or the relative elevation of the site contrary to popular belief.

Electrical resistivity methods are by far the most widely used technique for assessing ground water potential in this part of the world. In an effort to identify geoelectrical parameters which have a bearing on ground water availability, several hundred vertical electrical soundings were analysed and correlated with borewell data at the respective site. The result of the analysis indicates that geoelectrical parameters such as formation resistivity and total longitudinal conductance are not appreciably affected by the ground water availability from a given geological section. It is seen that this ambiguity is due to the fact that the water bearing formation fractures at depths of 20 m and more are relatively thin, about a few tens of centimetres in thickness, and they do not appreciably alter the overall resistivity. Added to this is the reality that a thick weathered zone does not necessarily mean more ground water, hence even a thick low resistivity layer cannot be taken as a definite indicator of a prolific aquifer. The study has highlighted the need for an integrated approach, where a detailed hydrogeological knowledge of the area must form the basis for interpreting geoelectrical data and locating sites for the construction of borewells.

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LIST OF PARTICIPANTS

Dr. Frank J. Anderson
Senior Staff Scientist
Regulatory Affairs
6220 Culebra Road
San Antonio, Texas
78228-0510 USA
[illegible]

Dr. Mary P. Anderson
Department of Geology & Geophysics
University of Wisconsin - Madison
215 West Dayton
Madison, Wisconsin
53706 USA

Dr. Sylvia Bachu
Alberta Geological Survey
Alberta Research Council
PO Box 8330, Station F
Edmonton, Alberta
T6H 5X2 Canada

Professor Allan Bell
Department of Geology & Geophysics
University of Wisconsin - Madison
1215 West Dayton
Madison, Wisconsin
53706 USA

Dr. Peter B. Bailey
ABB Environmental Services Inc.
101 Commercial St.
PO Box 9000
Portland, Maine
04112 USA

Dr. Scott D. Blair
Hydrogeologist, Cook County
[illegible]
Chicago, Illinois
[illegible]

Dr. P. W. Cleveland
Department of Applied Geology
University of Newcastle
Shortland
New South Wales
[illegible]

Dr. Paul Bertram
Brown & Ferriman
500 - 100 - 1500
Calgary, Alberta
T2P 0M5 Canada

Mr. Ron Bonnett
Chevron Canada Resources
500 Fifth Avenue SW
Calgary, Alberta
T2P 0L7

Dr. Stan Bridges
Water Commission
Wisconsin Department
Hydrogeologist
[illegible]

Dr. [illegible]
Geologic Survey
1577 Dolphin Drive
Winnipeg, Manitoba
R3E [illegible]

Mr. Bob Bowerman
Ontario Ministry of Natural Resources
Geological Survey
900 Bay Street, Main Floor
Toronto, Ontario
M7A 1C2 Canada

Mr. Gary Boyd
Total E&P Canada
Suite 2400, 425 - 1st Street SW
Calgary, Alberta
T2P 3L8 Canada

Mr. Ron Brown
Environmental Department
Vancouver Island
[illegible]

[illegible]

[illegible]

[illegible]

Dr. Holger H. Hartmaier
Acres International Ltd.
Suite 600, 10201 Southport Road SW
Calgary, Alberta
T2W 4X9, Canada

Mr. Robert Hawkes
Fekete Associates Inc.
#2000, 540-5 Avenue SW
Calgary, Alberta
T2P 0M2, Canada

Mr. John Heller
PBCC
New Mexico Institute of
Mining and Technology
Socorro, New Mexico
87801, USA

Mr. Joost Herwaijer
GeoTrans Inc.
250 Exchange Place, Suite A
Herndon, Virginia
22070, USA

Dr. Brian Hitchon
Alberta Geological Survey
Alberta Research Council
PO Box 8330, Station F
Edmonton, Alberta
T6H 5X2, Canada

Mr. Ken Hugo
Esso Resources Canada Ltd.
Box 2480, Station M
Calgary, Alberta
T2P 3M9, Canada

Professor Elizabeth Jacobson
Desert Research Institute
University of Nevada
7010 Dandini Blvd.
Reno, Nevada
89506-0220, USA

Ms. Janice Keppel
Canadian Hunter
435-2th Avenue SW
Calgary, Alberta
T2P 3A9, Canada

Dr. Peter K. Kitanidis
Water Resources
Department of Civil Engineering
Terman Engineering Center
Stanford University
Stanford, California
94305-4020, USA

Dr. Sam Kocabas
Research and Engineering
5445 DTC Parkway
Englewood, Colorado
80111, USA

Dr. John Kramers
Alberta Geological Survey
Alberta Research Council
PO Box 8330, Station F
Edmonton, Alberta
T6H 5X2, Canada

Dr. Larry Lake
Department of Petroleum Engineering
The University of Texas at Austin
CPE 2.502
Austin, Texas
78712, USA

Mr. Pat Lapointe
National Water Research Institute
867 Lakeshore Road
Burlington, Ontario
L7R 4A6, Canada

Mr. Bernard Lefebvre
Alberta Environment
11139-34A Avenue
Edmonton, Alberta
T6J 1M3, Canada

Mr. Bruce Manchon
International Technology Corporation
4585 Pacheco Blvd.
Martinez, California
94553, USA

Dr. Emanual Mazor
The Weizmann Institute of Science
Isotope Department
76100 Rehovot, Israel

Mr. R.R. McGillivray
Department of Geophysics & Astronomy
University of British Columbia
2219 Main Mall
Vancouver, British Columbia
V6T 1W5, Canada

Mr. G.S. McNab
Esso Petroleum Canada Ltd.
3535 Research Road NW
Calgary, Alberta
T2L 2K8, Canada

Dr. V.A. Mironenko
Mining Institute
Tyrsikaja 18 ap. 52
Leningrad 19324, USSR

Ms. Gerlynn R. Moline
Department of Geology & Geophysics
University of Wisconsin - Madison
1215 West Dayton
Madison, Wisconsin
53706, USA

Dr. Jesper Bruun Nielsen
Danish Land Development Service
Fiskerivangen 3
Slangerup 3550, Denmark DK

Mr. Manos Noore
Department of Civil Engineering
Graduate Office
University of Waterloo
200 University Avenue West
Waterloo, Ontario
N2L 3G1, Canada

Mr. Scott Parker
Hazardous Materials Management
Magazine
12 Salem Avenue, Suite 200
Toronto, Ontario
M6H 4C2, Canada

Dr. Elkin Pelaez
Colorado School of Mines
Golden, Colorado
80403, USA

Mr. James S. Brown
Southern Company Services, Inc.
PO Box 2625
Birmingham, Alabama
35202, USA

Dr. Malcolm Reeves
Geological Engineering Department
University of Saskatchewan
Saskatoon, Saskatchewan
S7N 0W0, Canada

Mr. Jeff Riddle
Salt River Project
PO Box 52025
Phoenix, Arizona
85072-2025, USA

Dr. Robert Ryall
Department of Geological Sciences
Wright State University
Dayton, Ohio
45435, USA

Ms. Carol Rix
Canadian Hunter Exploration Ltd.
435 4th Avenue SW
Calgary, Alberta
T2P 3A8, Canada

Mr. Craig Robertson
Monenco
801 6 Avenue SW
Calgary, Alberta
T2P 3W3, Canada

Mr. Ben Rostron
Department of Geology
University of Alberta
1-26 Earth Sciences Building
Edmonton, Alberta
T6G 2E3, Canada

Mr. Timothy D. Scheibe
Department of Civil Engineering
Stanford University
Terman Engineering Center
Stanford, California
94305-4020, USA

Dr. Rainer Senger
Bureau of Economic Geology
The University of Texas at Austin
University Station, Box X
Austin, Texas
78713-7508, USA

Ms. Lisa D. Shepherd
Department of Geology & Geophysics
University of Wisconsin - Madison
1215 West Dayton
Madison, Wisconsin
53706, USA

Mr. C. Steven Simmons
Battelle PNL
MS K6-77
Richland, Washington
99352, USA

Mrs. Kathie Skogg
Alberta Geological Survey
Alberta Research Council
PO Box 8330, Station F
Edmonton, Alberta
T6H 5X2, Canada

Dr. Leslie Smith
Department of Geological Sciences
University of British Columbia
Vancouver, British Columbia
V6T 2B4, Canada

Mr. Richard D. Stoberry
J.B. Butler and Associates
PO Box 23526
Tampa, Florida
33623, USA

Dr. David Thomson
Environmental Engineering
Research Department
Alberta Research Council
PO Box 8330, Station F
Edmonton, Alberta
T6H 5X2, Canada

Mr. Bryan J. Travis
Earth and Environmental
Sciences Division
MS-F665
Los Alamos National Laboratory
Los Alamos, New Mexico
87545, USA

Mr. Mark Truden
Environmental Engineering
Research Department
Alberta Research Council
PO Box 8330, Station F
Edmonton, Alberta
T6H 5X2, Canada

Mr. Mark Justian
Amoco Canada
240 - 8th Avenue SW
PO Box 200, Station M
Calgary, Alberta
T2P 2H8, Canada

Mr. Jim Underschultz
Alberta Geological Survey
Alberta Research Council
PO Box 8330, Station F
Edmonton, Alberta
T6H 5X2, Canada

Mr. Cor van Kruysdyk
Shell Canada Ltd.
8655 - 36 Street NW
Calgary, Alberta
T2P 3S8, Canada

Mr. Ian van Staalduinen
Canadian Hunter Exploration Ltd.
435 - 4th Avenue SW
Calgary, Alberta
T2P 3A8, Canada

Mr. Steve Velman
Esso Resources Canada Ltd.
Box 6001
Calgary, Alberta
T2P 2J2, Canada

Mr. Erik K. Webb
Department of Geology and Geophysics
University of Wisconsin at Madison
215 West Dayton Street, Weeks Hall
Madison, Wisconsin
53706, USA

Dr. John T. Wilson
New Mexico Institute of
Mining and Technology
Socorro, New Mexico
87801, USA

Mr. Glen Winner
Alberta Environment
Groundwater Rights Branch
2nd Floor, 9820 - 106 Street
Edmonton, Alberta
T5K 2J6, Canada

Dr. Kevin K. Wolka
Geraghty and Miller, Inc.
50 West Big Beaver Road, Suite 145
Troy, Michigan
48084, USA

Mr. Jianrai Xiang
Department of Mineral Engineering
104 Mineral Sciences Building
Pennsylvania State University
University Park, Pennsylvania
16802, USA

Mr. E.N. Yearsley
COLOG, Inc.
Borehole Geophysical Services
1019 8th Street, Suite 100
Golden, Colorado
80401, USA

Mr. Steven O. Young
Engineering Laboratory
Tennessee Valley Authority
129 Pine Road
Norris, Tennessee
37828, USA