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Meetings

Meeting Report

Chapman Conference on Spatial Variability in Hydrologic Modeling*

The AGU Chapman Conference on Spatial Variability in Hydrologic Modeling was held July 21–23, 1981, at the Colorado State University Pingree Park Campus, located in the mountains some 88.5 km (55 miles) west of Fort Collins, Colorado. The conference was attended by experimentalists and theoreticians from a wide range of disciplines, including geology, hydrology, civil engineering, watershed science, chemical engineering, geography, statistics, mathematics, meteorology, and soil science. The attendees included researchers at various levels of research experience, including a large contingent of graduate students and many senior scientists.

The conference goal was to review progress and discuss research approaches to the spatial variability of catchment surface and subsurface properties in a distributed modeling context. Mathematical models of water movement dynamics within a catchment consist of linked partial differential equations that describe free surface flow and unsaturated and saturated flow in porous media. Such models are utilized extensively in attempts to understand and predict the environmental consequences of human activities such as agricultural land management, waste disposal, urbanization, etc. We are concerned with the spatial structure of the parameters in such models, the precipitation input, and the geometric complexity of the system boundaries. The emphasis of this conference was on surface and subsurface hydrological process and their interactions.

Until recently, there has been little development of spatial analyses in hydrology. In the last 4 years, groundwater hydrologists have pioneered the representation of aquifer parameters as the realization of two- or three-dimensional random processes, and the precipitation process has been described as a random field in space and time. The physics of water flow in the unsaturated zone in a heterogeneous, porous medium is particularly difficult because the water content tension and water content conductivity relationships must be considered as random functions. There has been little interaction between surface and subsurface hydrologists in establishing the appropriate time and space scales required to couple surface and subsurface models.

A substantial number of field data sets documenting spatial variability are now available. Although these data have been useful in describing the structure of the parameter and functional fields in the saturated and unsaturated zones, more effort is needed to use this information to devise a series of researchable questions about the distributed modeling of hydrologic systems. We hope that this conference will stimulate such activities. A major challenge to the research community is to incorporate the observed regularities in soil characteristics, stream channel networks, basin form, and geological formations, along with statistical information on variability within units, into an objective technique for spatial representation of watershed systems.

Rafael Bras (MIT) set the tone for the conference by reviewing the often conflicting conclusions of recent investigators on the importance of spatial variability of rainfall and the resulting precipitation excess on catchment response. He outlined a new distributed linear approach to estimating catchment response to rainfall excess, exploiting the basic order in stream systems as reflected in geomorphological indices. He found that—with a homogeneous random input—as the spatial correlation increased, the output variance increased (i.e., the more noisy the rainfall, the better behaved was the output). A similar result for catchments with uniform rainfall but spatially varied hydraulic resistance was reported by Wu, Woolhiser, and Yevjevich (CSU and ARS-USDA).

Comprehensive, physically based, distributed hydrologic models were described by E. Morris (Institute of Hydrology) and by J. C. Refsgaard (Technical University of Denmark and Danish Hydraulic Institute). The data requirements for such models, at any practical spatial grid size, emphasize the need to understand the parameter variability expected at subgrid scale and also points out the need for objective techniques that simplify the mathematical representation of hydrologic systems.

Several investigators reported the results of field measurements of hydrologic properties of soils. Several Utah State investigators made direct measurements of the spatial variability of infiltration by using ring infiltrometers. R. J. Wagenet found that steady state infiltration rates were log normally distributed, and optimal infiltrometer spacing could be determined from regionalized variable theory. Grah and Hawkins examined the relationship between infiltration rate and overland flow distance to the nearest channel. B. J. McGurk reported work by Gifford, Bowles, and Springer on spatial variation of infiltration from a plowed and seeded pasture and a native sagebrush site. M. Vauclin, G. Vachaud, and J. Imbernon (Institut de Mecanique de Grenoble) found that for a 1-ha plot in Senegal the percent silt and clay has some correlation structure for $x < 40$ m, but that other factors, such as sorptivity, steady state infiltration rate, volumetric water content, and hydraulic head, had no apparent spatial structure. Data presented by D. Fritton (Pennsylvania State University) illustrated the serious problems involved with the description of the soil water regime for plant growth models. P. Germann, K. Beven, and R. Clapp (University of Virginia) presented a geostatistical analysis of soil moisture data obtained from a three-dimensional grid at a forested site in Switzerland. Variograms demonstrated that correlations first decreased and then increased with horizontal distance, suggesting some large-scale spatial structure.

Watershed scale variability in soil moisture was described by M. E. Hawley, T. J. Jackson, R. H. McCuen, and G. A. Coleman (University of Maryland and ARS-USDA), and some simplified approaches to characterize spatial variability of soil water properties at this scale were presented by J. W. Naney and L. R. Ahuja (ARS-USDA). The effects of soil moisture variability on runoff were presented by B. J. McGurk (Utah State University), using the Stanford runoff model, and by H. A. Wilkening and R. Ragan (Univ. of Md.) using a numerical solution of the Richards equation. W. J. Rawls and D. Brakensiek (ARS-USDA) reported the hydrologic characterization of some 4000 sets of soil water retention data from 1000 soils in 35 states. The Brooks and Corey parameters were estimated and transformed to normal distributions, and means and variances were obtained for each soil textural class.

Spatial variability of soil properties often has a more significant effect on the transport of chemicals and sediments than on surface runoff response. A. Rogowski (ARS-USDA) used geostatistical methods to analyze the spatial structure of erosion loss from a strip-mined watershed, while J. B. Laronne and S. A. Schumm (Ben Gurion University and CSU) evaluated the variability of salt content in surface soil layers. T. S. Steenhuis and R. E. Muck (Cornell University) developed a mathematical model that distinguished between transport in soil macropores and micropores to describe nonhomogeneous water and nonadsorbed nutrient movement in soils underlain by a hardpan.

K. E. Bencala and R. A. Walters (USGS) found that a transient storage model described field data of solute transport in a pool and riffle stream much better than the simpler convective dispersion model. E. Hoehn (Stanford University) described the effect of spatial variation of hydrogeological parameters on the transport of water and solutes from a river into an underlying aquifer. R. H. B. Hebbert and R. E. Smith (University of Western Australia and ARS-USDA) provided an excellent transition between discussions of surface and subsurface hydrology by presenting a simplified, physically based model in which surface, unsaturated zone, and saturated zone hydraulics are interactively linked. The model was used to demonstrate the effects of random distributions of several sensitive catchment properties. In all cases, the response properties are poorly represented by model results that use mean parameter values because of process nonlinearities.

Although the emphasis of this conference was on surface and subsurface hydrological processes, a few papers on rainfall were included. J. S. Gibbons and K. Adamowski (McNeely Engineering Ltd., and University of Ottawa) described the application of space-time autoregressive moving-average

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(STARMA) models to generate precipitation fields in time and space. G. Tabios and J. Salas (CSU) found that kriging and optimal interpolation techniques were superior to other methods commonly used to estimate annual precipitation at ungaged sites. S. Shih (University of Florida) presented a new method of determining the number of gages necessary to estimate mean watershed rainfall with a confidence level provided for the accuracy of the estimate. J. Harlin and J. Salisbury (University of Oklahoma) used factor analysis to determine the attenuation characteristics of a large watershed, and K. Beven and G. Hornberger (University of Virginia) found that storms of different spatial patterns resulted in outflow hydrographs with quite different peak timing characteristics, but that differences in the distributions of peak flow and flow volumes were generally insignificant for the Illinois watersheds studied.

Leslie Smith (University of British Columbia) presented the second keynote paper on spatial variability in the saturated and unsaturated zones. Using field data from the Quadra Sand, a stratified unconsolidated sand outcropping near Vancouver, Canada, as an example, he demonstrated the geostatistical techniques used to describe the spatial variability of such properties as porosity and hydraulic conductivity. He emphasized the continuing need for data sets that characterize the spatial variability of porous media from different geological environments and on a variety of scales; said data to be used in evaluating theoretical models. He also pointed out the need to improve field techniques for obtaining estimates of required statistical parameters, noting that horizontal continuities are especially difficult. Finally, he called for new methods of designing sample grids so as to reduce uncertainties in model prediction.

E. Bresler, D. Russo, and G. Dagan (Volcani Center and Tel Aviv University) measured saturated hydraulic conductivity, water entry pressure, saturated and residual water content, and sorptivity. Parameters characterizing the pore-size distribution were calculated. Each of the seven parameters was described as a realization of a stationary, two-dimensional isotropic random process characterized by density functions independent of spatial position and by autocorrelation functions between any two spatial points in the field. For their field study they found that autocorrelation functions approached zero at about 90 m, and the integral scale ranged from 25 to 75 m. T. Yeh and L. Gelhar (New Mexico Tech) analyzed the effects of spatial variability of parameters on unsaturated flow by solving stochastic steady state infiltration partial differential equations. They found that the head variance derived for three-dimensional flow analyses is less than that of one-dimensional flow. Also, as the correlation length scale for saturated hydraulic conductivity and a water characteristic parameter increase, the one- and three-dimensional results converge, indicating that one-dimensional flow predominates. J. Batardy, M. Dehon, O. Cogels, and L. DeBacker (University of Louvain) described a statistical procedure to reduce the number of soil-moisture-measuring sites required to estimate watershed recharge.

In saturated porous media flow systems, hydraulic conductivity and porosity can be treated as a realization of a three-dimensional stochastic process. P. Kitanidis and E. Vomvoris (University of Iowa) used a first-order analysis to derive the statistical properties of the associated nonstationary random fields of piezometric head and specific discharge from solutions of the stochastic partial differential equations for steady flow in finite equifers. They found that ratios of scales of parameter fluctuations to corresponding formation dimensions determine the variability of the piezometric head and discharge and also provide a criterion for the suitability of the first-order analysis. S. Mizell, L. Gelhar, and A. Gutjahr (EG&G and New Mexico Tech.) used spectral analyses techniques to investigate steady flow in infinite aquifers. They found that head fluctuations exhibit correlation over greater distances than log transmissivity and are reduced as the dimensionality of the system increases. G. Dagan (Tel Aviv University) used a perturbation approximation for unsteady flows in one, two, and three dimensions. He concluded that for slowly varying flows in space and time a time-dependent, effective transmissivity can be defined. It approaches a steady state value after a relaxation time.

The inverse problem of determining aquifer transmissivity from piezometric observations was attacked by C. Daly (USA-CRREL) on the basis of harmonic analysis. The piezometric and transmissivity fields are assumed to be smooth, and the remaining nonuniqueness is overcome by specifying transmissivity along a curve intersecting all stream lines. M. Aboufirassi and M. Marino (University of California, Davis) demonstrated an application of the kriging technique in transmissivity identification. G. Chirlin (Princeton) questioned the validity of current hypotheses about porous medium heterogeneities, i.e., piecewise, smooth, or stationary random, and described as an example a spatially periodic medium with clay lamina that has some geological justification and can become a building block for a heterogeneous medium. Field measurements of fracture systems in intrusive rock masses and statistical methods for describing the interconnectivity of these fractures so as to develop a probabilistic description of directional permeabilities were discussed by A. Rouleau and J. Gale (University of Waterloo).

The problem of solute transport in heterogeneous aquifers was considered on a theoretical basis by several investigators. G. Dagan (Tel Aviv University) obtained a closed-form solution for the concentration expectation in two-dimensional flows from which he concluded that the concept of dispersivity is generally meaningless for two-dimensional flows. E. Lightfoot, T. Hatton, E. Stoll, and M. Anderson (University of Wisconsin) discussed the conceptual problems associated with the pseudo continuum approximations to the diffusion equation and the potential utility of solutions based on modifications of the random walk model for dispersion in heteorogeneous media. T. Hatton and E. Lightfoot demonstrated the utility of the approach, based on generalized Taylor dispersion theory, to identify the dispersion characteristics of horizontally stratified aquifers. P. Bro (Cornell University) presented an analysis of leaching with probabilistic flux, and C. Simmons (Battelle Northwest) analyzed column tracer experiments by a stochastic convective flow equation. D. Leland and D. Hillel (Arthur D. Little and University of Massachusetts) presented the results of tracer tests in a shallow, sloping unconfined aquifer.

A comprehensive, but highly simplified model of the hydrologic cycle and a pollutant cycle, to provide exposure assessment analysis of chemicals in the hydrologic system, was presented by J. Wagner and M. Bonazountas (Arthur D. Little). The application of kriging in analyzing concentrations of zinc in coal mine overburden was presented by A. Jones, D. Bowles, and R. Wagenet (Utah State University).

The final keynote presentation, by L. Gelhar (New Mexico Tech), on 'Stochastic Problems and Methods of Dealing with Spatial Variability in Hydrologic Modeling,' brought many seemingly diverse papers into clear perspective. He first posed the relevant questions regarding the impact of spatial variability, e.g., How does spatial variability affect the design and interpretation of field experiments, the average or bulk behavior of models and parameters, and the variability of model predictions? He then briefly reviewed the development of statistical and stochastic methods in analysis of spatial variability (primarily in groundwater) and described the significant results and applications to field studies and network design. A. Gutjahr (New Mexico Tech) described the use of kriging and cokriging, along with stochastic differential equations for one- and two-dimensional stationary groundwater flow cases. A most interesting aspect is that the method yields an indication of the worth of data and where and what kinds of additional observations should be made to minimize the variance of the estimators.

A. Mantoglou and J. Wilson (MIT) compared the Turning Bands Method (TBM) to other methods of generating multidimensional random fields. They found it to be as accurate as, and far less expensive than, other techniques.

On the final afternoon of the conference, discussion centered on the use of remote sensing techniques to obtain input data for distributed hydrologic models and on data management techniques to efficiently manipulate the large amounts of data required for such models.

J. Fellows (University of Maryland) presented a computer-based watershed development system that utilizes USGS-DEM digital terrain tapes and can develop a digital binary picture of a watershed and its stream network when the user inputs the location of the outfall cell. R. J. Gurney and T. J. Schmugge (NASA/Goddard Space Flight Center) discussed the remote sensing of soil moisture, which is important for initializing distributed hydrologic models. They presented examples of estimation of soil moisture variations, using airborne thermal infrared and passive microwave sensors. They also described the use of remotely sensed measurements of soil moisture in the optimal design of conventional soil moisture measurement networks. R. Ragan and J. Fellows (University of Maryland) considered the requirements of interfacing remote sensing and information management data, using the 1036-km^2 (400-mi^2) Montgomery Co., Md., data as an example. Geographic information systems, utilizing triangular and rectangular grids, coupled with distributed hydrologic models were described by W. Grayman and R. Males and J. Sarsenski, P. Koch, and W. Grayman (W. E.

Gates and Associates); and W. Striffler (CSU). T. Croley III (NOAA) described a computer algorithm for automatically ordering computations for a distributed surface runoff model consisting of a network of spatially uniform elements.

Panel discussions, ably chaired by D. Nielsen (University of California, Davis), H. Morel-Seytoux (CSU), and A. Gutjahr (New Mexico Tech), were held at the end of the sessions each day to raise questions or point out omissions in the day's discussion and to relate the material to previous or subsequent topics.

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This meeting report was prepared by D. A. Woolhiser and H. J. Morel-Seytoux, convenors.