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Hydrology

Progress and Opportunities in Hydrologic Research, 1987-1990

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INTRODUCTION

This Report documents the U. S. National Report for Hydrology to the International Union of Geodesy and Geophysics (IUGG) for the quadrennium 1987-1990. The report consists of nine papers covering various aspects of the hydrological sciences, including global-scale hydrology, catchment hydrology, surface water modeling, snow and ice research, and subsurface water flow and contaminant transport. The papers reveal many opportunities for innovative research in the hydrologic sciences. These opportunities are predicated, among other things, by the introduction of new methods for modeling and measuring water and contaminant processes in naturally heterogeneous soil and groundwater systems, and by increased emphasis on global-scale processes motivated in part by concerns about global climate change.

Research during the past quadrennium has been stimulated greatly by growing awareness that our ability to measure, model and manage surface and subsurface hydrologic processes is complicated by the extreme heterogeneity of the hydrological environment. This heterogeneity manifests itself on a variety of scales, ranging from small-scale heterogeneous subsurface flow and transport processes and material properties to large-scale spatially and temporally variable surface and subsurface phenomena. Some of the issues of heterogeneity in subsurface flow and transport are brought up by *Sudicky and Huyakorn* [1991], and are described in more detail by *Wang* [1991] and *Wheatcraft and Cushman* [1991] from different perspectives. The problem of heterogeneity has also resulted in the development of a large number of stochastic models and statistical data collection protocols, and has stimulated the development of improved instrumental techniques for more accurate measurement of physico-chemical processes and relevant hydrologic parameters. Another theme common to all nine papers of this Report is the realization that future progress in many areas of hydrologic research requires a more multidisciplinary approach, and that disciplinary boundaries are becoming increasingly fuzzy.

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For convenience I have divided the papers in two broad categories: surface hydrology and subsurface hydrology. The surface hydrology papers comprise the contributions by *Wood* [1991] on global-scale hydrology, *Westerink and Gray* [1991] on surface water modeling, *Goodrich and Woolhiser* [1991] on catchment hydrology, and *Richter-Menge et al.* [1991] on snow and ice research. The subsurface hydrology papers are by *Gee et al.* [1991] on flow and transport processes in the unsaturated zone, *Sudicky and Huyakorn* [1991] on contaminant transport in the saturated zone, *Wang* [1991] on flow and transport in fractured rock, and *Wheatcraft and Cushman* [1991] on transport in heterogeneous media from a more general perspective. The Report concludes with a discussion by *Dane and Molz* [1991] on physical measurements in subsurface hydrology. Readers are encouraged to study all papers and not just those that appear within their own field of interest.

SURFACE HYDROLOGY

The review by *Wood* [1991] on global-scale hydrology focuses on the representation of land-surface hydrologic processes in general circulation models for prediction at regional, continental and global scales, and on field studies over a range of scales insofar as they impact hydrological processes at the larger scales. Wood states that whereas the land surface component of global hydrology has long been an active research area for meteorologists and climate modelers, hydrologists have only recently become actively involved in this area of research. He cites a previous report by *Eagleson* [1986] to reiterate the educational implications of increased global climate research to hydrologists. For example, hydrologists are becoming increasingly cognizant of the importance of radiation physics, geophysical fluid dynamics, precipitation processes, micrometeorology, plant physiology, and ecology, in global-scale hydrologic research. Progress also requires the development of improved physically-based models for biosphere-atmosphere interactions to estimate the transfer of energy, mass and momentum between the atmosphere and the vegetated surface of the earth. Improvements in quantifying soil water dynamics should lead to improved climate simulation studies and related analyses of climate sensitivity and change. Among the issues to be studied with biosphere-climate models are the large-scale climatic effects of deforestation and the loss of tropical rain forests.

Goodrich and Woolhiser [1991] in their review of catchment hydrology point out that important progress has been made in integrated mathematical modeling, but that a detailed process-based understanding of hydrologic response over a range of catchment scales (0.01 - 500 km^2) is still lacking. Progress in water quality and global climate research requires a commensurate effort in catchment hydrology. For example, future research in catchment modeling must address the problem of permissible system and model complexity, the scales over which model components are valid, and the integration of model components into an overall balanced framework. Integrated models also cannot ignore the sources of uncertainty resulting from by ill-defined input and system parameter distributions. Several innovative techniques for treatment of catchment variability have been developed during the past four years. Hybrid schemes now exist which incorporate both stochastic and deterministic components. Proper treatment of the spatial and temporal variability of catchment parameters and processes remains one of the most challenging areas of research in catchment hydrology. Parameters and processes controlling hydrologic response operate at many different time and length scales. A consistent treatment of these processes requires that the scales of measurement and modeling be commensurate. *Goodrich and Woolhiser* [1991] also note the continued progress in automation of catchment modeling and database management, as was foreseen four years ago by *Wallis* [1987]. However, Goodrich and Woolhiser also caution that improvements in the resolution of catchment descriptors (topography, soils, vegetation), and in the speed of retrieving information, will not necessarily lead to improved hydrologic predictions unless more appropriate models are developed and used. These observations are consistent with those of *Burges* [1986] who states that only minimal progress is likely when methods which were useful before the availability of computers are being programmed for computer use. The greatest progress should come from efforts which recognize that computers are machines that augment the human mind, and that computers are much more than large, fast calculation devices.

Similar comments about computer modeling, model validation and automation apply to surface water hydrology. *Westerink and Gray* [1991] note that the past quadrennium has seen the development of more sophisticated computational schemes which take advantage of rapidly increasing computer power. These schemes include more comprehensive fundamental equations describing the underlying physical processes, improved formulation of applicable boundary conditions, and state-of-the art numerical finite difference and finite element techniques which better describe the geometry of the simulated region. Additionally, more attention is being paid to model verification. Significant efforts were made during the past quadrennium to compare the numerical accuracy of selected models, and the ability of these models to match measured data sets. In spite of these efforts, *Westerink and Gray* [1991] also believe that surface flow modeling is not yet a solved problem. For example, they expect in the coming years a much greater degree of model interfacing, such as the coupling of shelf/coastal models with surface water circulation models, in addition to the development of more comprehensive models with a much broader scope and purpose. These expectations parallel those expressed by *Wood* [1991] who foresees an improved treatment of the biosphere-atmosphere boundary in global climate models, and *Goodrich and Woolhiser* [1991] who advocate an improved linkage of the surface water and groundwater components in watershed models.

Snow and ice research during the past quadrennium has covered a wide range of topics including the climatic effects of large ice sheets and sea ice covers, the electromagnetic properties of snow and its implications to measuring snow properties, snow pack energy exchange, the chemistry of snow packs, and a number of applied topics such as the icing of power lines and communication facilities. The review of *Richter-Menge et al.* [1991] focuses on three specific topics: remote sensing of polar ice caps (mostly using microwave instrumentation), ice mechanics, and seasonal snow covers. The authors use these topics as examples of the general needs in snow and ice research, notably: a better representation in models of the fundamental physical and chemical processes, carefully controlled laboratory experiments to better quantify the underlying processes, and field studies to interpret results from remote sensing techniques.

SUBSURFACE HYDROLOGY

Subsurface hydrology has received increased attention during the past quadrennium because of growing concerns about soil and groundwater pollution from industrial, municipal, and agricultural sources. *Gee et al.* [1991] concentrate on recent progress in the areas of stochastic and deterministic modeling of vadose zone transport processes, laboratory and field experiments for model validation, multiphase flow, solute transport through soil macropores or other preferred pathways, and measurement of soil heterogeneity in general. The dramatic shift in hydrologic research from water supply studies toward analyses of contaminant migration continued during the past quadrennium. Federal, state and local action and planning agencies, as well as the public at large, are becoming increasingly concerned about water quality issues. A variety of U. S. governmental and other agencies are now supporting several large field studies designed to improve and test models that predict water and contaminant transport in naturally heterogeneous soils. These and other studies are important for checking the validity of classical Fickian-based advection-dispersion equations for predicting solute movement in laboratory and undisturbed field settings.

Considerable skepticism remains about the validity of the classical flow and transport equations, especially for near-saturated flow conditions. The classical equations are also not applicable to preferential flow caused by fluid flow through soil macropores, or induced by unstable flow or fingering in relatively coarse-textured materials. As a result, stochastic models of solute transport continue to be developed and used in the research community. There is also an increased interest in groundwater pollution problems caused by non-aqueous phase liquid (NAPL) organic chemicals that are immiscible with water. Of special environmental concern are dense nonaqueous phase substances such as halogenated solvents and polychlorinated biphenyls (see also *Sudicky and Huyakorn* [1991], as well as *Abriola* [1987] in the previous IUGG report). The past quadrennium has seen the development and testing of several multiphase flow and transport codes that address a range of near-surface organic liquid contamination and remediation scenarios, such as possible ways of removing volatile organic compounds from soil using air-stripping techniques. Companion efforts to the modeling work have been theoretical and experimental attempts to quantify the constituent hydraulic relationships for multiphase flow, including the hysteretic nature of multiphase liquid systems. *Gee et al.* [1991] conclude that field studies and simulation of single and multiple phases and constituents, methods of interpreting and applying the characteristics and spatial structure of field data, and development of new instrumentation and procedures for measuring the hydraulic and chemical properties of soils are all areas of research that will continue to provide challenges to vadose zone hydrologists.

Sudicky and Huyakorn [1991] in their paper on groundwater contamination focuses on the effects of geologic heterogeneity on contaminant migration in groundwater, and on developing models and methods for quantifying the effects of heterogeneity on subsurface solute transport. They stress that the natural heterogeneity of geologic materials is a major obstacle to obtaining reliable predictions of plume evolution, and to designing effective detection, monitoring and aquifer remediation strategies. A variety of stochastic-analytic modeling approaches now exist for describing solute transport in heterogeneous geologic materials. These models make use of effective, field-scale water flow and solute dispersion parameters derived from geostatistically estimated properties of the underlying permeability heterogeneity of an aquifer. The use of effective transport parameters is essential for performing large-scale transport simulations because of our inability to measure point-to-point variations in the hydraulic and geochemical properties of individual geologic units over large transport distances. While a number of stochastic theories have been developed, the need remains to test competing models by means of carefully executed field and laboratory tracer experiments. Tracer studies performed under controlled conditions are extremely valuable for understanding processes governing the transport, dispersion, reaction, and biotransformation of contaminants in soil and groundwater systems, provided the studies are accompanied by detailed characterization of geologic materials within which the experiments are conducted.

One of the main issues that continues to be debated by soil physicists and groundwater hydrologists is the space and time-dependent nature of the dispersion process. The debate of how to characterize spatial variability continues. Recent work in stochastic modeling focuses not only on predicting the expected concentration from average field-scale parameters, but also on methods that quantify the prediction uncertainty caused by imprecise or insufficient knowledge of the real hydrogeologic system. This uncertainty results from a lack of understanding of the underlying physical, chemical and biological processes (model uncertainty), and from uncertainty in the initial, boundary and system parameters. Prediction uncertainties have a direct bearing on the design of waste management facilities and the establishment of regulatory policies, as well as the optimal design of aquifer remediation strategies to reduce the risk of failure.

Sudicky and Huyakorn [1991] also review recent advances in the development of numerical solution techniques for detailed simulation of water flow and contaminant transport processes in the subsurface. These advances include the development of more efficient matrix solution techniques for transport problems with a large number of nodal unknowns (e.g., 1 million), multi-grid numerical methods, preconditioned conjugate gradient solutions for solving large sparse matrix equations, development of more stable numerical schemes for advection-dominated transport (such as the Laplace Transform Galerkin Method), and development of multiphase flow and transport models.

The effects of hydrogeologic heterogeneity on water flow and contaminant transport in fractured rocks is discussed by *Wang* [1991], mostly from a deterministic and process-oriented manner. He points out that earth scientists have made significant progress in the quantitative description of flow channeling and solute breakthrough in rough-walled fractures, in analyzing transitions between fracture and matrix flows under multiphase conditions, and characterizing fracture networks using hydrological and geophysical studies. Wang also discusses the repercussions of heterogeneity on contaminant transport at various scales. In particular he notes that many common features can be identified for microcracks, discrete fractures, soil macropores, fractured rock masses, and heterogeneous reservoirs at different scales. The presence of heterogeneity at various scales is addressed by *Wheatcraft and Cushman* [1991]. They review several methods which may be used to quantify heterogeneity, especially when one moves hierarchically from one scale of observation to another at a larger scale. While several methods have been developed to connect heterogeneity at sequentially larger scales, one of the most popular and convenient conceptual formulations is the fractal-mathematical model which leads to scale-dependent material properties. Wheatcraft and Cushman give an excellent picture of how to view and quantify subsurface heterogeneity in a (dis-)orderly fashion; their assessment will be appreciated by all readers, and particularly the non-expert reader.

This Report concludes with a very relevant discussion by *Dane and Molz* [1991] on physical measurements in the saturated and unsaturated zone. The authors emphasize that complex mathematical models can only make realistic predictions if the representative values of the hydraulic properties, including those of unsaturated soils, are available. While a number of instrumental techniques (notably surface and subsurface geophysical methods) and measurement methodologies (including inverse procedures) have been developed or improved during the past quadrennium, many challenges remain to accelerate much-needed progress in this area of research.

CONCLUDING REMARKS

The 1987-1991 quadrennium has seen much progress in hydrologic research and understanding of hydrologic phenomena at a variety of scales. Foremost, the problem of medium heterogeneity continues to play an often frustrating role in the areas of predictive modeling and measurement technology. The enormous variability of the hydrologic environment, and the imprecision with which parameters and processes can be measured, has led to the adoption of stochastic models and geostatistical procedures to assist in the prediction and monitoring of the hydrologic system. Increased awareness of the importance of heterogeneity will undoubtedly kindle additional developments in modeling, measurement, and management technologies. Hence, the challenges for both fundamental and applied research are numerous, as is the need for young researchers who are fascinated by the complexities of imperfectly understood hydrologic systems, and who have the necessary educational background and determination to respond to these challenges. Additional efforts are needed, not only to improve existing models and measurement methodologies, but also to develop radically new alternatives in modeling and measurement. These efforts may include "small science" research work by individuals or small teams of scientists who are motivated primarily by curiosity about how nature works (as articulated eloquently by *Dalrymple* [1991]), as well as large and more comprehensive, mission-oriented interdisciplinary group research efforts as envisioned by *Wallis* [1987] in the previous IUGG Report. Clearly, much remains to be done. As such, I hope that this Report will provide a useful assessment of the major current challenges in hydrologic research, and that the Report will inspire new and imaginative research during the next quadrennium and beyond.

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