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Recent advances and themes in hydrology

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Introduction

The twenty-three review articles which follow provide a compendium of recent advances over the last quadrennium, 1991-94, which relate to some of the scientific, technologic, and policy aspects of the field of Hydrology. Due to space and time limitations, neither the titles of the review articles chosen for this report nor the review articles themselves are exhaustive, instead they are only intended to provide an overview of some recent advances in hydrology. A more exhaustive review of research agendas relating to the scientific aspects of hydrology may be found in a recent National Research Council report [*NRC,* 1991]. An exhaustive review of the current state of hydrologic practice may be found in the new *Handbook of Hydrology* [*Maidment,* 1993].

This introductory paper provides a selective and cursory summary of the key points raised by the authors of the following reports, and some introductory comments.

Water: An International or National Crises?

As the field of hydrology approaches the millennium, one expects more and more noticeable water resource impacts on society resulting from increasing world population, political and economic instabilities increasing regulatory pressures and possibly anthropogenic driven climatic change [*Wallis,* 1993]. When one reads the titles of a few recent treatises on water problems: *Water—The International Crisis* [*Clarke,* 1993], *Water in Crisis* [*Gleick,* 1993], one obtains an attitude of doom. Some of the facts support this view. A 1975 survey by the World Health Organization (WHO), which covered 90% of the developing countries (excluding China), showed that only 35% of the global population had access to relatively safe drinking water and only 32% had proper sanitation. In other words, about 1.2 billion people lacked safe drinking water and about 1.4 billion people lacked sanitation [*Clarke,* 1993]. Total water use in the world has quadrupled during the last fifty years [*Clarke,* 1993]. *Gleick* [1993] compiles enough up-to-date statistics on our planet's demand for, and supply of water to resolve most debates on the subject. *Clarke* [1993] documents an international water crises, yet U.S. water problems are quite different. Environmentalists tend to see our own water resources in dire straits yet those who favor economic development see no need to restrain further usage. *Rogers* [1993] argues that when one examines each case in detail, whether irrigation, domestic supply, or wildlife support, there are usually good alternatives available to us, often at a small cost, hence the U.S. does not face a water crises when compared to the entire globe.

Moreau [this issue] documents the relative stability of U.S. water policy over the past decade as evidenced by level spending for water projects and declining support for wastewater treatment plants in an effort to reduce the federal budget deficit. In contrast, spending by local governments and sewer services continue to rise. Yet concurrently, there have been few reductions in the requirements for drinking water safety or protection of overall ambient water quality.

After the disastrous 1993 Mississippi river flood, *Moreau* [this issue] documents that the federal government increased its attention to zoning, relocation, floodproofing and restoration of natural storage in the nation's wetlands instead of reliance on levees and other flood control structures. Demand management programs and overall water-use efficiency programs have become accepted practice and effective for long-term water supply planning in lieu of the tradition of using them only in drought emergencies. *Moreau* [this issue] further documents that nonpoint sources are now the leading cause of pollution in streams and lakes in the country, with agriculture cited as the dominant source. An emerging theme in U.S. water policy and management appears to be a return to what was once called integrated or unified river basin management and is now couched in terms of watershed management and sustainable development [*Newson,* 1992].

Recent Advances Associated With Hydrologic Modeling

General Issues

Recent advances in computer technology have led to a proliferation in the development of decision support systems (DSS). *Watkins and McKinney* [this issue] define a DSS as an integrated, interactive computer system, consisting of analytical tools and information management capabilities, designed to aid decision makers in solving relatively large, unstructured problems. There are many examples of DSS in the field of water resources, yet the most rapid growth has occurred during this past

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quadrennial see *Watkins and McKinney,* [this issue]. Most DSS have integrated some combination of classical water resource simulation and/or optimization models, database management systems, geographic information systems (GIS), expert and knowledge-based systems, multiobjective decision support tools and graphical user-friendly interfaces. *Watkins and McKinney* [this issue] argue that recent developments associated with our ability to access and process very large spatially distributed databases over high-speed and readily accessible networks offers tremendous potential for the development of DSS during the next quadrennial. In addition, improvements in our ability to process very large distributed sources of remotely-sensed and space-based hydrologic and climatic data [*Engman,* this issue] combined with advanced data assimilation algorithms [*McLaughlin,* this issue] should lead to benefits in both theoretical and applied hydrology. *McLaughlin* [this issue] suggests that ultimately, data assimilation efforts in the field of subsurface hydrology should be analogous to similar efforts in such fields as geophysics, seismology, and petroleum engineering, to name a few.

Remotely-sensed and space-based observations are particularly important in snow-cover studies due to the difficulty of making field measurements in snow-covered mountainous regions. *Bales and Harrington* [this issue] review the application of various image-processing methods for use in measuring snow cover properties.

Hornberger and Boyer [this issue] argue that "creation of, application of, and squabbling over mathematical models of watershed processes have been favorite pastimes of hydrologists for many decades." There are many new sources of information which result from recent advances in remote sensing [*Engman,* this issue], such as digital terrain data and the use of chemical and isotope data. Nevertheless, *Hornberger and Boyer* [this issue] argue that many major problems still exist for those wishing to compute the hydrologic response of a watershed. They argue that there is a need to improve our "empirical" understanding of watershed processes through experimental studies similar to those reviewed by *Kustas* [this issue] and *Engman* [this issue]. Such empirical studies should not be viewed as "less scientific" than more mathematical types of research and inquiry.

Most of the following review articles focus on either subsurface or surface water, yet the interaction between these two hydrologic fields cannot be ignored. Due to concerns relating to acid precipitation, eutrophication, land development and water allocation, *Winter* [this issue] argues that understanding the relationship between subsurface and surface water is a field ripe for future multidisciplinary interactions among hydrologists, geochemists, and biologists because the biogeochemical processes within the upper few decimeters of sediment beneath nearly all surface water bodies can have a profound effect on the chemistry of groundwater entering surface water, as well as on the chemistry of surface water entering groundwater. *Winter* [this issue] provides an overview of both analytical and numerical procedures for describing the interaction between groundwater and surface water in a variety of landscapes.

Recent Advances in Understanding Land/Atmospheric Interactions

Entekhabi [this issue] documents how atmospheric processes propogate through the complete regional hydrologic system and vice versa. Both *Entekhabi* and the *NRC* [1991] report, *Opportunities in the Hydrologic Sciences,* firmly establish that since the atmospheric forcing of surface hydrologic processes depends upon the land surface conditions, a two-way land-atmospheric interaction exists. *Bales and Harrington* [1994] also emphasize the importance of quantifying energy fluxes across the land-atmosphere because of their dominant role in snowpack evolution and meltwater generation. Since the land, biosphere, atmosphere and ocean systems are coupled across a wide range of spatial and temporal scales, each scientific discovery tends to lead to a deeper and larger scientific question [*Entekhabi,* this issue].

Spatial variability of land surface processes affects the dynamics of the atmosphere (and vice versa) at different scales. *Avissar* [this issue] argues that an important hydrologic challenge is to develop a soil-vegetation-atmosphere-transfer scheme (SVATS) which can provide the characteristic length scale of the land-surface patchiness and the distribution of surface heat fluxes. To obtain the distribution of heat fluxes required, Avissar argues that such hydrologic SVATS schemes will likely require high-resolution topography, soil texture and vegetation type. At the global scale, development of such data sets remains an enormous challenge. *Avissar* [this issue] further argues that since such high-resolution macroscale field experiments are not likely to be available in the foreseeable future, we will have to rely on theoretical analyses, for the moment, to guide more focused field experiments. Nevertheless, Entekhabi argues that some of the new large-scale data sets (also see *Kustas* [this issue], and *Engman* [this issue]) combined with the scientific questions raised in his review and posed by the *NRC* [1991] should lead to advances in our understanding of the coupled land-atmosphere interaction.

Recent Advances in Subsurface Hydrology

Aquifer simulation models are important tools for managing groundwater resources. *Wagner* [this issue] describes numerous studies in which aquifer simulation models have been combined with optimization methods for the purpose of designing aquifer remediation plans, managing pumping and injection systems, evaluating groundwater policies, controlling aquifer hydraulics, preventing saltwater intrusion and for the optimal allocation of surface and groundwater resources. *Wagner* [this issue] laments, as did *Rogers and Fiering* [1986] for surface water optimization problems a decade ago, that given the plethora of applications of systems methodologies in the literature, there are conspicuously few studies which describe the implementation of groundwater management strategies derived from the combined use of simulation and optimization models. Interestingly, a decade after the *Rogers and Fierings* [1986] criticisms, the combined use of simulation and optimization is now almost routinely applied in industry, for example, to hydropower scheduling problems. Perhaps it takes a few decades of research applications until such procedures find their way into actual practice.

Much of the research in the area of groundwater modeling focuses on the important problem of designing aquifer remediation systems [*Wagner,* this issue; *Rathfelder et al.,* this issue]. For example, soil vapor extraction (SVE) is now a fully established and widely exploited groundwater remediation technology [*Rathfelder et al.,* this issue]. Further advancements in SVE, bioventing and other subsurface remediation technologies will result from future advances relating to the description of heterogeneous soil properties and fluid distributions and from advances relating to the accurate mathematical description of non-equilibrium mass exchanges between phases and microbial degradation kinetics.

The development of accurate models for the prediction of multiphase multicontaminant transport in groundwater will require advances in a variety of different areas. *Russell* [this issue] provides an overview of recent practical models of multiphase multicontaminant transport in groundwater along with a discussion of the experimental and theoretical issues relating to the formulation and application of mathematical models. *Celia et al.* [this issue] describe recent advances in the use of pore-scale models for describing multi-phase porous media systems.

Again, as argued earlier by *Hornberger and Boyer* [this issue] significant advances in our understanding of subsurface heterogeneity are likely to result from data-driven studies such as isotope and environmental tracer studies [*Phillips,* this issue]. It is encouraging to observe an increasing number of studies which employ isotopic and environmental tracers in addition to other investigative techniques for exploring subsurface flow regimes [*Phillips,* this issue]. Field studies which reflect the full spatial and temporal heterogeniety of the subsurface are increasingly exploiting scale invariance to reduce the complexity of large databases. *Sposito* [this issue] provides an encouraging review of vadose-zone hydrology, when he notes that both empirical and theoretical studies are exploiting scale invariance leading to a connection between field and theoretical studies which has provided deeper insight into the mechanisms of soil water processes at field scales.

On another scale, *Person and Baumgartner* [this issue] summarize our current state of knowledge relating to regional and long-distance fluid migration within the earth's crust. Their review demonstrates that shallow groundwater flow systems are expected to receive considerable and significant fluid input if they are above active metamorphic and tectonic terrains.

Recent Advances in Statistical Methods

An emerging theme related to the use of statistical methods in hydrology is the development of nonparametric methods for frequency analysis, spatial curve fitting, trend analysis, hypothesis testing, regression, time-series analysis, simulation, and other problems [*Helsel and Hirsch,* 1992; *Lall,* this issue]. Nonparametric procedures afford significant advantages over their parametric counterparts. Nonparametric procedures generally reproduce the empirical structure of multivariate data sets yet they do not require assumptions about data or model structure, nor do they require parameter estimation. Therefore, nonparametric procedures do not suffer from the usual attendant losses associated with having chosen an incorrect model and used an inefficient parameter estimation algorithm. As a result, simple data resampling schemes such as the bootstrap and jackknife are beginning to become accepted by hydrologists [*Kitanidis,* this issue; *Lall,* this issue] as conceptually simple (yet computationally intensive) alternatives to more complex parametric alternatives. On the one hand, *Lall* [this issue] argues that the literature on nonparametric function estimation has historically been very mathematical, yet in the simplest case, a moving-average, long accepted by practitioners, provides an illustrative example of how palatable nonparametric methods really are to practitioners. Together, *Helsel and Hirsch* [1992] and *Lall* [this issue] provide a comprehensive review, introduction, and comparison of nonparametric and parametric statistical procedures applied to a wide class of water and environmental applications. *Maidment* [1993, Chapters 17-19] also provides a comprehensive review of statistical methods useful in water resource investigations.

The challenges posed by extreme hydrological events continue to vex hydrologists. The introduction of the theory of L-moments [*Hosking,* 1990] is probably the single most significant recent advance relating to our understanding of extreme events. Generally, L-moments are linear combinations of ordered observations, which are unbiased regardless of the parent population, hence L-moments allow us to discriminate the behavior of skewed hydrologic data which was difficult or impossible only a few years ago. *Bobee and Rasmussen* [this issue] and *Maidment* [1993, Chapter 18] review the theory and application of L-moments. It is no longer adequate to base our understanding of extreme events on a single sample of streamflow. *Bobee and Rasmussen* [this issue] document advances in the use of regional information to improve our ability to understand and predict extreme events. Naturally, improvements in our ability to predict extreme events will ultimately come from improvements in our understanding of the physical processes along with improvements in regional statistical methods.

Recent statistical research has greatly improved methods for estimating sediment and nutrient transport in rivers. *Cohn* [this issue] argues that the bias of rating curve estimators can now be eliminated and a new unbiased and efficient approach based on stratified random sampling has emerged making it possible to design relatively low-cost sampling programs for measuring sediment and nutrient transport.

Innovations in statistical methodologies in hydrology are probably exemplified by the role of geostatistical methods in hydrogeology. Geostatistical methods continue to be developed for a wide range of new and old hydrogeological problems. *Kitanidis* [this issue] warns us that there is no scarcity of sophisticated techniques, yet their use is not always tempered with a basic understanding of statistical methods and common sense. Many successful methods that appear under different names in different fields are basically the same [*Kitanidis,* this issue; *McLaughlin,* this issue]. There is a trend to develop Bayesian, data assimilation and other regional methods which can integrate many sources of information.

Recent Advances in Hydrologic Forecasting

In general, improvements in real-time hydrologic modeling and forecasting will depend upon developments related to numerical weather prediction models, watershed modeling, remote sensing methods, and methods for handling the space-time variability of rainfall at various scales. *Foufoula-Georgiou and Krajewski* [this issue] review advances related to rainfall modeling, estimation, and forecasting. *Krzysztofowicz* [this issue] reviews developments relating to flash flood forecasting, main-stem flood forecasting, and flood warning systems. *Krzysztofowicz* [this issue] documents the relatively recent developments in flood forecasting relating to the coupling of flood forecasting systems with flood warning decisions and emergency response plans. In some sense, these integrated flood forecasting/warning/response systems described by *Krzysztofowicz* [this issue] are good examples of an emerging class of decision support systems described by *Watkins and McKinney* [this issue]. As significantly more data become available with, for example, the implementation of the Next Generation Weather Radar (NEXRAD) system over the entire U.S., our understanding of the space-time variability of rainfall at various scales should improve.

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