An Agenda for Land Surface Hydrology Research and a Call for the Second International Hydrological Decade

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ABSTRACT

Hydrologic research at the interface between the atmosphere and land surface is undergoing a dramatic change in focus, driven by new societal priorities, emerging technologies, and better understanding of the earth system. In this paper an agenda for land surface hydrology research is proposed in order to open the debate for more comprehensive prioritization of science and application activities in the hydrologic sciences. Sets of priority science questions are posed and research strategies for achieving progress are identified. The proposed research agenda is also coupled with ongoing international data collection programs. The driving science questions and related research agenda lead to a call for the second International Hydrologic Decade. This activity will help to ensure that hydrology starts the new millennium as a coherent and vital discipline.

1. Background

Hydrologists are facing important, even fundamental, changes in the direction of their science. New tools, nontraditional datasets, and a better understanding of the connection between hydrology and the rest of the climate system are being developed just as society's needs for improved water management and hazards prediction are becoming critical. The application of new ideas and techniques to the difficult hydrologic problems of the future will require a carefully formulated plan of attack.

Water at the land surface is a vital resource, both for human needs and for natural ecosystems. Society's growing water resource needs include hazard mitigation (floods, droughts, and landslides), agriculture and food production, human health, municipal and industrial supply, environmental quality, and sustainable development in a changing global environment. Desertification and drought are problems of global dimension that affect more than 900 million people in 100 countries. Irrigation already accounts for more than 70% of freshwater withdrawn from lakes, rivers, and groundwater aquifers, and perhaps 80% of the additional food supplies required to feed the world's population in the next 30 years will depend on irrigation (UN-SWI 1997). Today, about one-third of world's population live in countries that are experiencing moderate to high water stress, that is, renewable freshwater availability is below 1700 cubic meters per

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person. By 2005, projections suggest that one-fifth of the global population will not have access to safe drinking water, and more than one-half will lack adequate sanitation (UN-SWI 1997).

Despite the emergence of advanced technology both developed and developing countries will probably feel the effects of limited freshwater resources in the near future. Economic growth and social welfare in major urban centers of the semiarid United States and other megacities in the industrialized and industrializing worlds will be affected by hydrometeorological hazards as well as by limited water availability. In fact, floods and droughts are considered by some to be the leading natural threats to society in many countries (NRC 1996). Global environmental changes brought about by land-use modifications, desertification, and anthropogenic greenhouse trace gas emissions are intimately connected with water at the land surface. The ultimate impact of such changes is highly uncertain and difficult to predict.

The new hydrological tools available to address water resource problems are largely a reflection of technological advances in environmental monitoring and computation. Satellite remote sensing provides, for the first time, the potential for global coverage of critical hydrological data (e.g., precipitation, soil moisture, and snow water content). Such global data are logistically and economically impossible to obtain through traditional in situ measurement. However, remote sensing datasets are in forms unfamiliar to many hydrologists, largely because the measured quantities are radiances that are only indirectly related to the hydrologic variables of most interest. Computational advances have made it possible to develop new data processing and assimilation techniques that are able to extract useful information from these indirect measurements.

In addition to new types of data, hydrologists are encountering a new intellectual paradigm that emphasizes connections between land surface hydrology and other components of the earth system (NRC 1991). This coupling is now widely considered to be essential. It has already led to significant changes in the research and training foci for the discipline.

The continuing shifts in hydrology, driven by new tools and intellectual paradigms, should not take place blindly. The hydrological community must take stock of the current state of knowledge, prioritize the emerging science questions for the coming decade, set objectives, and identify data needs and standards. This paper, which proposes an agenda for land surface hydrology research at the beginning of the new millennium, is a response to the challenge facing the hydrologic community. The authors collaborated voluntarily, and no institution or agency supported or commissioned the work. Our purpose is not to claim the agenda but to open the debate. Although our scientific priorities are focused on the land surface–atmosphere continuum, the authors hope that this initiative may serve as an example for other areas of hydrology. The land surface hydrology agenda we propose originates in the science questions posed in section 2. These questions reflect ideas and experiences communicated through the existing hydrologic literature. For the sake of clarity, and in order to reduce the need for expanded discussions, the science questions are raised and discussed without specific references. These questions imply a whole set of data and modeling needs that will require commitment of both economic and human resources. In section 3 we explore these needs and identify important priorities for hydrologic research and development.

In section 4, we propose a concerted effort to answer the science questions and to achieve the research objectives we have identified. We call this effort the Second International Hydrological Decade (2d IHD). The 2d IHD is intended to engage the research community in its efforts to develop effective tools for translating of data into useful information. Key objectives of the proposed 2d IHD are 1) to develop feedback between the research community and agencies responsible for water-related research and 2) to provide an intellectual framework that can be used to guide management decisions, including decisions related to the allocation of research funds.

Land surface hydrology is a discipline through which many of the emerging advances in monitoring, computation, and telecommunications may be brought to bear on food supply, health, security, and development issues facing Earth's growing population. This promise may only be realized if hydrologic data collection and modeling activities are based on sound scientific principles. This is the overall objective of the scientific agenda we propose.

2. Priority science questions

a. What are the mechanisms and pathways by which the coupling between surface hydrologic systems and the overlying atmospheric modulate weather and climate variability?

The exchanges of moisture and energy between soil, vegetation, and snowpack and the overlying atmospheric boundary layer have impacts on near-surface atmospheric moisture and temperature. These in turn largely define regional climate. For example, when soil moisture or plant stomatal closure limit latent heat flux, the near-surface atmospheric humidity deficit and temperature are increased. This leads, in turn, to elevated growth of the boundary layer and enhanced entrainment of relatively warm and dry air. The overall process constitutes a positive feedback mechanism for continued surface drying.

The behavior introduced by such multivariate coupling and feedback may lead to excursions, oscillations, and persistence of hydroclimatological anomalies (e.g., extreme precipitation, droughts, etc.; see Fig. 1). These phenomena cannot be accounted for in analyses or models that force the various components of the land–air system in isolation. The contributions of land–atmosphere coupling to regional anomalies such as continental droughts (e.g., 1970s Sahel or 1988 U.S. Midwest) and large-scale flooding precipitation events (e.g., 1993 U.S. upper Midwest) need to be established and quantified. Both observations and models can help in this endeavor. The timescales associated with the surface and subsurface storage of moisture depend in complex ways on both climate and geology. These connections need to be clarified if we are to develop a better understanding of connections between the landscape, hydrologic response, and the persistence of climate anomalies.

Hydrologic states that have long memory or serve to integrate past atmospheric forcing may be used to enhance prediction skill for regional climates. For example, the short-term evolution of weather events is affected by fluxes (e.g., summertime precipitating convection) that depend on surface states such as soil moisture and temperature. Figure 2 shows the gains in forecast skill brought about by the introduction of improved land surface characterization and initialization in an operational numerical weather prediction model. At longer lead times, deeper soil storage and plant root distribution may affect prediction skill. Studies of surface and subsurface water budgets are needed to better describe the surface water–groundwater interactions that operate over these longer timescales.

It should be recognized that hydrologic states such as soil moisture and snow cover influence the surface flux of moisture and energy only under a limited set of conditions that depend on surface properties and atmospheric forcing (see Fig. 3). There are timescales (i.e., storm, interstorm, and seasonal) and geographic regions in which fluxes of moisture and energy are essentially independent of land surface moisture.

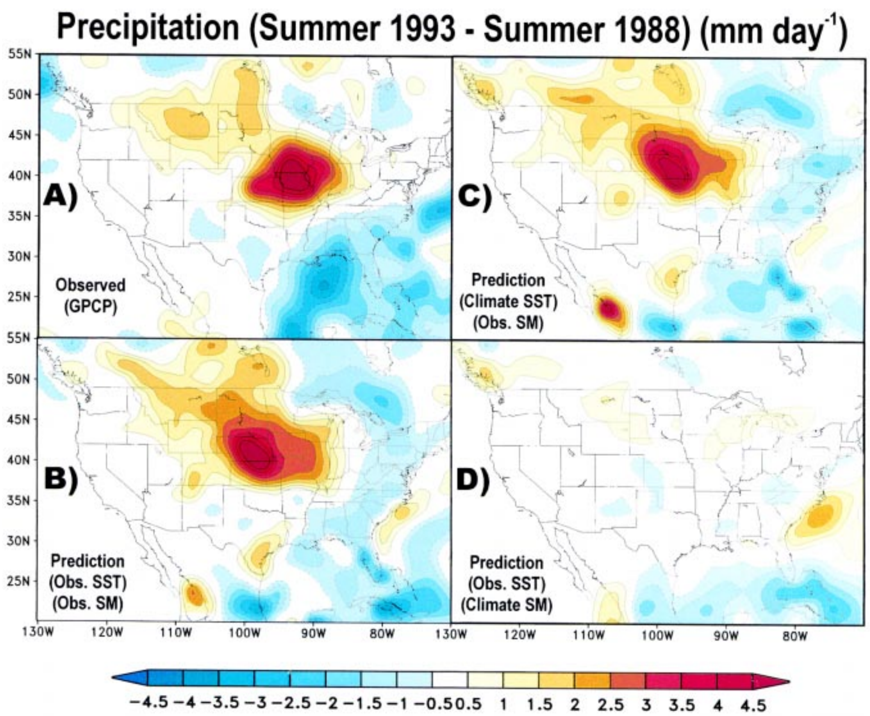

FIG. 1. Relative influences of sea surface temperature (SST) on boreal summer precipitation. (a) Observed precipitation over the continental United States for summers containing the extreme 1988 drought and 1993 flood events are presented as a difference field. (b), (c), (d) General circulation model results for the same differences between rainfall during the 1993 flood and 1988 drought events are shown. (b) Both SSTs and soil moisture fields are either observed or estimated for the specific period of simulation. (c) Estimates of soil moisture for the particular time period are used in conjunction with SST climatology. (d) Observed SSTs are used as boundary condition for the simulation in conjunction with estimated soil moisture climatology. This figure demonstrates both the impact of soil moisture on the numerical forecasting of the extreme events and the notion that surface soil moisture is equivalent in importance to SST as boundary conditions for the climatic system. It is evident that precipitation extremes over the United States are more strongly affected by soil moisture fields than SSTs, which are currently the principal fields used to extend forecast lead times (M. Suarez, S. Schubert, and A. Chang 1999, personal communication).

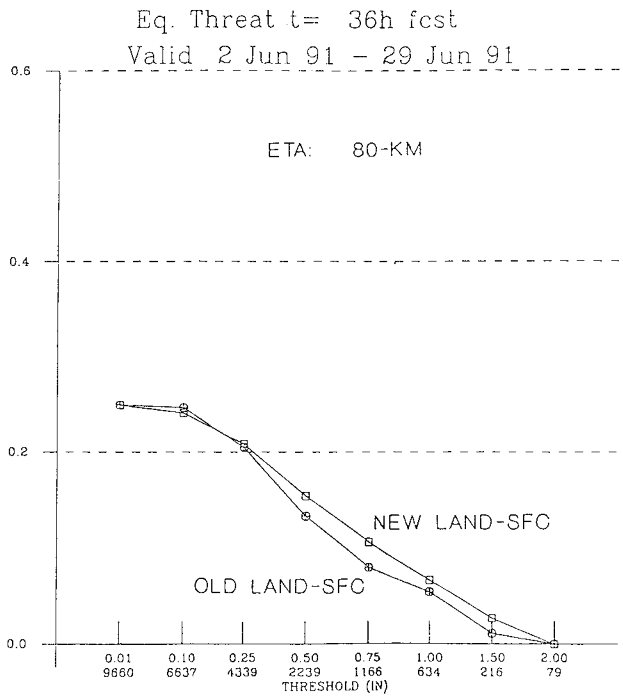

FIG. 2. Threat scores (a measure of forecast skill) for 36-h forecasts of 24-h accumulated precipitation as a function of precipitation threshold. The bottom curve shows the relationship obtained when the prediction system uses a standard bucket model initialized with climatological soil moisture values. The upper curve shows the relationship obtained when the bucket model is replaced by a more sophisticated land surface scheme and the soil moisture is more realistically initialized from reanalysis data. The combination of improved model physics and improved initial conditions for soil moisture has led to significantly improved weather prediction. The improvement seen here is of the same order as that obtained from doubling the resolution of the atmospheric model (K. Mitchell 1999, personal communication).

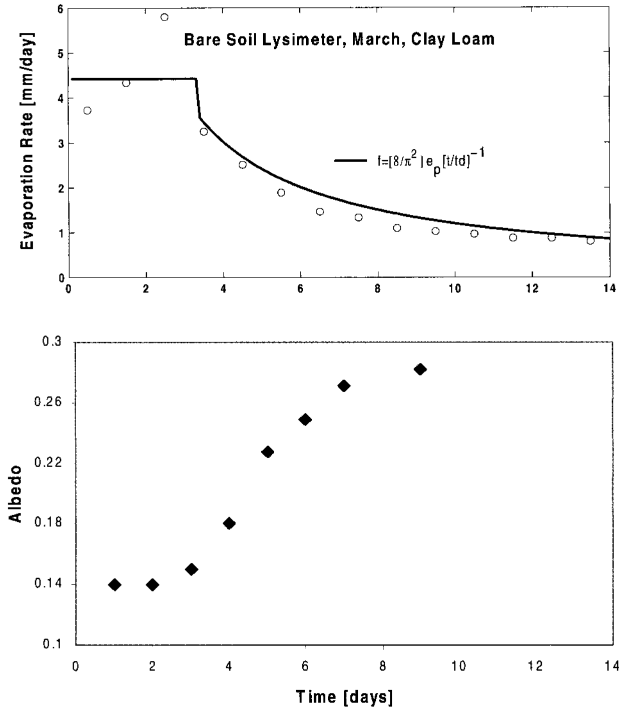

FIG. 3. Evaporation following rainstorms and soil wetting proceed through several stages. In the first stage, although soil moisture is steadily depleted by evaporation (equal to the so-called potential evaporation, e_p), the rate of evaporation is limited only by available energy to vaporize liquid soil water and it is essentially independent of soil moisture content. During the early period of the day or across high-latitude regions where available energy may be the limiting factor, this first phase may extend up to the next wetting event. Similarly, in climates with frequent wetting events, the first stage may dominate much of the time. During the second stage of evaporation, lower levels of soil moisture limit the movement of water in the soil to supply evaporation at the surface. The transition from the first to the second stage occurs at the time to drying (t_d), which depends on soil texture and climate. The figure shows field experiment observations by R. D. Jackson and the applicability of a model of the process by Salvucci (1997). The soil drying effect and the time to drying are evident in the albedo observations (lower plot). During this phase of evaporation soil moisture exerts strong influence on latent heat flux, surface energy balance, ground temperature, and the near-surface atmosphere states. In a third stage (not evident in this experiment), the evaporation rate is dominated by vapor flow driven by thermal gradients within the soil column. The influence of soil texture, vegetation, and atmospheric forcing on the timing of the transitions between evaporation regimes, and the effects of spatial and temporal aggregation on modeling the phenomena are not yet well established.

There is a need to identify and investigate climatic regimes that prevent surface conditions from influencing fluxes into the lower boundary of the atmosphere. The seasonal cycle and interannual variability of each of these regimes need to be understood as a prerequisite for predicting variability in regional climates.

A critical problem in coupled land–atmosphere process studies is the need to define appropriate system boundaries (see the heat and moisture budget example in Fig. 4). Air entrainment associated with the large diurnal variations of the atmospheric boundary layer is a significant factor in surface energy and mass balance. These processes need to be better understood if we are to substantially improve our ability to predict either atmospheric or land surface hydrologic processes.

Over larger scales and over longer periods, the convergence of moisture and static energy across the depth of the troposphere are strong constraints on regional hydroclimatology and on the atmospheric convergence of moisture and energy. Aspects of this effect may be monitored remotely (e.g., top-of-atmosphere radiation may be measured easily and accurately with

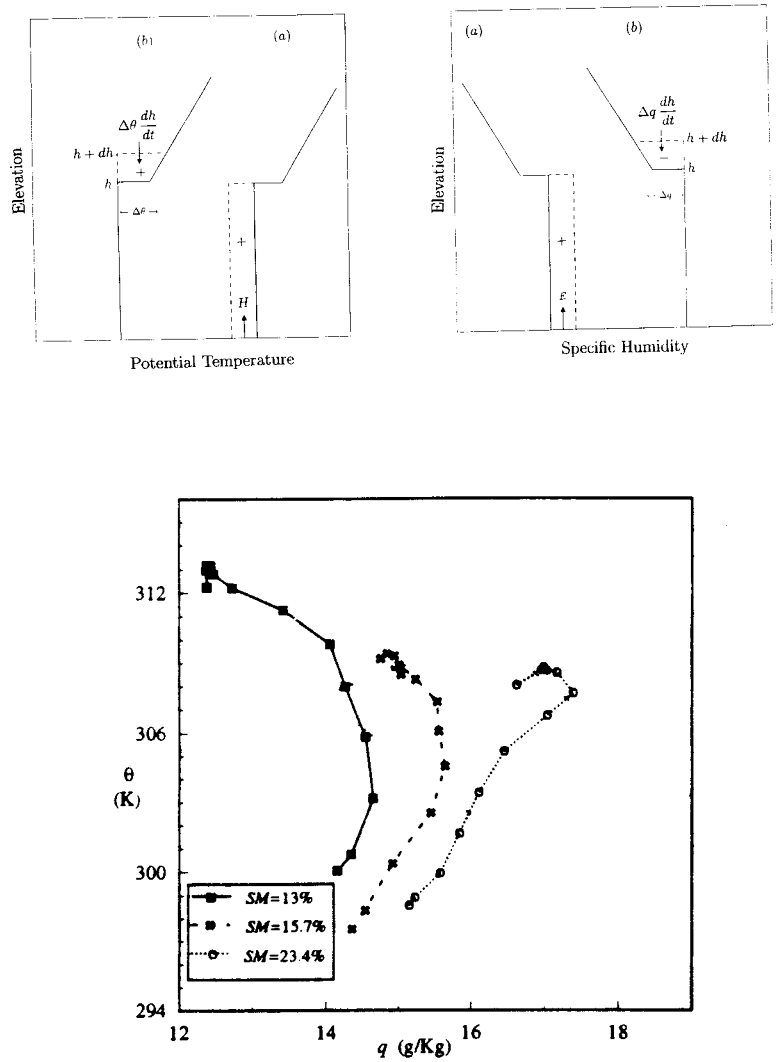

FIG. 4. Surface water and energy budgets are strongly coupled to the mixed atmospheric layer above the surface. In some applications it may be important to include the mixed layer water and energy budgets together with that of the surface. This is effectively redefining the control volume or the system boundaries for budget calculations. In the top panels the profiles of specific humidity (q) and potential temperature (θ) are shown conceptually for two time periods during the growth phase of the mixed layer. In plot (a) the results of surface input into the mixed layer are considered in isolation. Evaporation (E) and sensible heat flux (H) contribute to increase the q and θ of the mixed layer with height (h). If the h is fixed, the profiles of the variables at the new time follow the dashed lines. However, the h grows during the time period in response to thermals originating from near the surface. When the mixed layer grows to the new height ($h + dh$), dry and warm air is entrained into the mixed layer as depicted in plot (b). This growth in h contributes dry air to the mixed layer partially counteracting the moistening effect of surface evaporation. In contrast, the entrainment of air with higher θ from aloft, similar to surface sensible heat flux, contributes to increase the mixed layer θ. As a result, often times the diurnal range of q in the mixed layer is small and the diurnal range of θ is large. This is evident in the lower panel where averages of diurnal coevolution of the two variables are plotted for a set of days with different mean soil moisture (SM) but similar net radiation conditions across the First International Satellite Land Surface Climatology Project (ISLSCP) Field Experiment site in Kansas (from Betts and Ball 1995). The diurnal range of q is small and the curvature is reminiscent of the early-day evaporation input into a shallow mixed layer, and decrease during the latter part of the day when there is more rapid growth of the mixed layer into drier portions of the atmosphere. The potential temperature, θ, has a larger diurnal amplitude. The amplitude of the diurnal cycle in θ is larger for days with drier land surface conditions when the surface sensible heat flux and growth of the mixed layer due to thermals originating from the near surface are dominant factors. Since the surface turbulent fluxes (E and H) are driven by the gradient between the surface moisture and temperature states and those in the near-surface atmosphere, the coupled evolution of these states at the land surface and within the mixed layer may contain important feedback phenomena.

satellite sensors). Constraints on atmospheric convergence need to be better understood and, if possible, used to provide better estimates of fluxes in the atmospheric branch of the hydrologic cycle.

b. What are the mechanisms and the timescales of interactions between the formation of terrain, soils, vegetation ecotones, and hydrologic response?

The terrain, soil, and vegetation of the land surface all have important and direct effects on hydrologic response. Conversely, surficial hydrologic processes influence the development of these landscape characteristics. These mutual interactions between landscape, soil, and vegetation, on the one hand, and hydrologic processes on the other, occur over a wide range of timescales. In some cases the hydraulic properties of soils, including soil seals and macropores, may change over seasonal or annual scales in response to human activity. But soil conditions in environments not disturbed by humans seem to be controlled by longer-term processes that are driven by ecosystem change. The development of distinct soil horizons with different topographic contexts is a process that spans centuries.

Vegetation and hydrologic processes are linked over an even wider range of time- and space scales. A substantial fraction of the hydrologic exchange between the soil and the atmosphere is mediated by vegetation. Conversely, moisture availability is a key factor in the development and distribution of ecotones.

The representation of vegetation in hydrologic models and the consideration of its influence on the hydrologic cycle remain at rudimentary levels. Some possible areas of improvement include better representation of the limitations imposed by nutrient deficits. This will require incorporation of nutrient cycles, especially the nitrogen cycle, in models that account for coupling between hydrologic and ecological processes.

The commonly used resistance-network representation of plant control on moisture flux should be replaced with coupled physical and chemical models of water uptake by roots, moisture transport within xylem, and reaction processes within leaves. The physical characteristics and structure of vegetation stands need to be explicitly represented in ways that make it possible to directly observe model parameters with remote sensing instruments (e.g., lidar and radar). Furthermore, radiance measurements in regions of the spectrum where photosynthesis captures solar radiation should be used to provide strong constraints on land data assimilation algorithms in regions with vegetation cover.

In addition to studies of how plant physiology and transpiration respond on short-term timescales, investigations into the longer-term coevolution of ecotones and hydroclimate are needed. The amplitude of the components of surface water and energy balance depend on vegetation function. Furthermore, some interannual variability of hydrologic processes and, on paleotimescales, shifts in climate are associated with ecotone successions and variations. The nature of these associations needs to be understood, and their geologic and geochemical fingerprints need to be uncovered. The coevolution of the hydroclimatic and biospheric systems hints at the possibility (requires further study) that coupled ecological–climate models may in fact be affected by ecotone initialization, that is, different initial specification of vegetation types leads different equilibrium climate–vegetation regimes (Pielke 1998). We need to better understand the extent that different initial specifications of soils and vegetation can lead to distinct climatic regimes. This can be done with the help of long-term coupled models of climate, hydrology, and ecology.

Field experiments need to be conducted to clarify the many complex interactions among soil, vegetation, and hydroclimate. Coupled models need to be developed to reveal the effects of feedbacks, nonlinearities, and multiple timescales. Field and modeling studies should be directed toward a more integrated understanding of the genesis and joint evolution of topography, soils, vegetation, and hydroclimate.

c. Are there critical scales at which spatial variations in surface properties should be explicitly represented in models of land–atmosphere exchange? Can macroscale equations be formulated by upscaling process descriptions at the microscale and under what conditions can effective parameters be used to represent upscaled hydrologic processes?

Some hydrologic processes such as runoff are significant only because there is heterogeneity in the natural system. Most homogeneous soil textural classes have sorption rates that exceed generally observed rain intensities. They also have sufficient storage to contain an entire rainstorm. Nonetheless, flood runoff occurs due to the intermittent nature of rainstorms and the occurrence of low-permeability soil patches, rock outcrops, low transmissivity profiles, and high topographic convergence zones.

Temporal, as well as spatial, heterogeneity can be important in many hydrologic applications. In some cases, simple aggregation of temporal fluctuations can misrepresent important physical processes. For example, multistage evaporation and transitions from flux to ponding surface infiltration boundary conditions are processes that cannot be aggregated in time without introducing errors (see Fig. 3).

In all hydrologic investigations, it should be natural to first identify the critical time- and space scales at which heterogeneity should be explicitly represented. Such scales typically vary for each hydrologic process and for each application (see Fig. 5). There is a critical need to develop a systematic framework for the identification of critical hydrologic scales and the dependence of these scales on mean conditions. In many cases, including the runoff generation example given above, the relevant scales of natural heterogeneity span a wide range of time- and space scales. It is often not feasible to characterize variability over such wide ranges with available in situ or even remote sensing instrumentation. In such cases, models designed to predict macroscopic variables such as watershed runoff (e.g., hydrograph) need to account indirectly for the effects of unresolved heterogeneities. This process is frequently referred to as "parameterization" or "upscaling."

Successful field-scale parameterizations need to be based on a good understanding of microscale (often pore scale) physics as well as realistic characterizations of heterogeneity. They also should account for nonlinearities and scale interactions. A number of mathematical upscaling procedures have been applied in various branches of hydrology. In some cases, these procedures yield macroscale equations that have the same structure as microscale equations but with modified parameters. These "effective parameters" typically depend on the statistical properties of the unresolved heterogeneities as well as other site-specific variables.

For example, pedotransfer functions have been proposed as a means for assigning effective hydraulic properties to soils based on taxonomic units that are differentiated by parent geology, minerology, texture, bulk density, and organic matter content. These functions may be viewed as a first step in a sequential process of upscaling hydrologic processes from pore scales to hillslope scale. Nonetheless, important issues need to be resolved with respect to the design and application of pedotransfer functions. The effects of structured soils, soil chemistry, vegetation, climate, and topography all need further study. Also, attention should be devoted to methods for combining multitemporal and multispectral remote sensing with traditional sources of soil taxonomic data.

A number of theoretical and field studies have suggested that there may be hydrologic processes that elude upscaling with an effective parameter approach. Alternative procedures for upscaling microscale equations for such processes need to be established more formally than is done at present. The resulting field-scale models need to be tested with carefully designed experiments.

Although upscaling is required in many hydrologic applications, it should be noted that natural heterogeneity is often evident at scales that are close to the scale at which it is feasible to explicitly represent them in numerical models. Hydrologic processes that vary on scales that may be feasible to model explicitly include variations of snowpack with topographic aspect, variations of evapotranspiration with topographic gradients, variations in vegetation, boundary layer mixing and land-breeze circulations with surface cover changes, and variations of runoff with surface cover and topographic gradients.

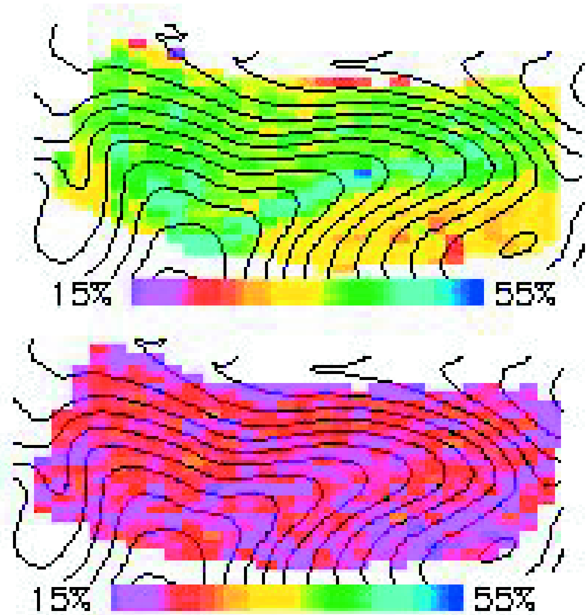

FIG. 5. High-resolution in situ observations of the soil moisture field in the small (0.1 km^2) Tarrawarra experimental catchment, southeastern Australia, demonstrates the role of competing hydrologic processes in defining spatial structures in the soil moisture field (Western and Grayson 1998). (top) The volumetric moisture content within the top 30 cm of soil during a typical wet season day (27 Sept 1995). In this case soil moisture pattern is organized by terrain elevation. The wetter zones follow elevation contours and drainage depressions. High hydraulic conductivity of moist soils allows significant redistribution along a topographic gradient. During a typical day in the dry season (22 Feb 1996 conditions shown in the bottom panel), there is no discerned correspondence between topography and soil moisture. Dry soil moisture has lower hydraulic conductivity and lateral redistribution is less dominant as a factor in organizing soil moisture patterns. The random spatial variability of soil texture may be a more critical factor in explaining any spatial variability in the soil moisture field. Lateral redistribution in the saturated and unsaturated zones, ground and surface water interaction, evapotranspiration, macropore flow, and soil texture heterogeneity are among the competing factors that influence the spatial organization of surface soil moisture fields. Detailed understanding of these processes and the development of parsimonious characterizations of them for inclusion in coarse-resolution models remain important challenges in land surface hydrology.

The identification of critical scales and related upscaling issues are problems that are directly relevant not only to the design of models but also to the design of in situ and remote observing systems, which may provide information at scales different than needed for modeling or other applications. These topics are also related to the question of how data should be interpreted, extended, aggregated, or disaggregated for various purposes. For these reasons, it is crucial that we develop a systematic framework for describing and detailing with the scale dependence of hydrologic phenomena.

d. Does lateral soil water redistribution significantly affect large-scale soil–vegetation–atmosphere exchange processes?

The partitioning of incident precipitation into runoff is dependent on near-surface processes that are significantly influenced by spatial interactions and lateral redistribution of moisture over complex terrain. Runoff-producing zones are limited to areas of low soil permeability, low gradient, and high moisture content. The latter source areas are primarily concentrated around the drainage network, either in convergent topographic regions that receive the gradient-driven lateral water movement in soils, or where the depression of the topographic surface decreases the storage capacity of the soil above the water table (see Fig. 5).

The representation of land surface hydrologic processes in spatially lumped (e.g., conceptual models used in operational hydrology and flood forecasting) or one-dimensional soil hydrology models (e.g., soil–vegetation–atmosphere transfer schemes used in numerical climate and weather forecast models) cannot, by construct, capture these important lateral redistribution processes. Instead, these models rely on calibration (or adjustment) of empirical parameters to reproduce observations of hydrologic processes over complex terrain. Without lateral redistribution through the regional groundwater system, flood runoff from large areas cannot be represented in a realistic manner by such models. The representation of lateral redistribution processes, groundwater, and surface water interactions should consider the time- and space scales of natural variations in topography, soils, vegetation, and climate.

Geochemical tracers are effective and sometimes underutilized tools for mapping lateral moisture movement in the subsurface. Identification of regional groundwater recharge and discharge zones, flow pathway studies, and hydrograph separation techniques benefit from simultaneous hydrologic and geochemical observations. Such observational capabilities, together with advances in computational capabilities, may be used to construct distributed hydrologic models that properly account for lateral flow. Such models can be used to assess the importance of lateral soil moisture redistribution and to clarify its role in runoff generation and the distribution of vegetation.

e. How can the effects of human activity on the landscape, its ecology, and hydrology be distinguished from natural climate variability?

Human modifications of the environment, includ-

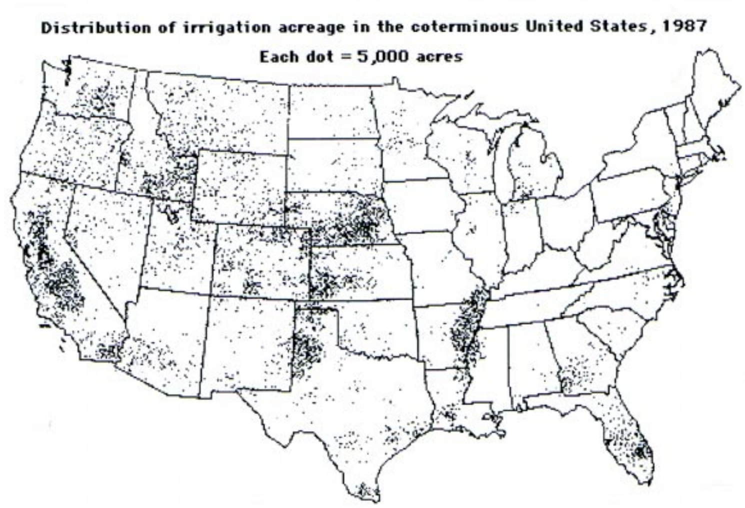

FIG. 6. Human land use practices can lead to significant changes in large-scale hydrological fluxes. The figure on the left shows mosaicked Landsat images of the Imperial Valley, on the border between California and Mexico (courtesy of U.S. Geological Survey Eros Data Center, Landsat images). Red indicates the presence of vegetation. The sharp southern edge of the red region corresponds to the California–Mexico border and thus reflects different land use practices in the two countries. Evaporation must be significantly higher north of the border. The figure on the right shows the extent of irrigation in the United States (Bajwa et al. 1992). The patterns suggest a large-scale human-induced increase in evaporation from the land surface, particularly in the arid West. The effects of this increase on large-scale weather patterns are unknown.

ing land cover change, irrigation, and flow regulation, now occur on scales that significantly affect seasonal and interannual hydrologic variations (see Fig. 6). However, long-term climate fluctuations and climate change are also major contributing factors to hydrologic variability. The partial (individual) contributions of human activity and climate variability need to be separated in the analyses of floods, drought, and other hydrologic phenomena. This raises methodological issues for both hydrologic data collection and modeling.

In the forthcoming decade, global change and its consequences will probably remain the major large-scale environmental issue. The hazards associated with global change are mostly realized through effects on the hydrological cycle and water availability. However, hydrologists have not yet developed the tools necessary to assess the possible impacts of climate change with enough certainty to enable managers and policy makers to benefit from current scientific and technical programs. Moreover, the lessons of past large-scale shifts in global and regional climates (e.g., paleoclimate variability and contemporary soil loss and desertification) and the role of hydrology in these analogs of global change have not been fully exploited. Finally, the feedback role played by the hydrological cycle in a changing climate has not been widely considered by the hydrologic science community (Chahine 1997). These three shortcomings in dealing with the global change problem need to be faced directly.

In the short term there is a need for robust statistical tests that can quantitatively identify the effects of human intervention from inherently noisy hydrologic data with multiple scales of variation (e.g., interannual and decadal). Care should be exercised in using hydrologic models to predict the human impacts on regional hydrologic processes. In particular, these models should be shown to be applicable to the regions where environmental conditions have changed. Also, investigators need to assess sources of prediction uncertainty and the relevance of current effective parameters for impact studies of changing environments.

In the longer term, climate models and models for regional hydrologic change need to converge and, in particular, account for the feedbacks and interactions that couple land surface, atmospheric, and oceanic processes. Both the developers and users of these models will need to exploit all available paleoclimatic and remote sensing data in order to clarify the respective roles of human activities and long-term natural fluctuations.

3. Implications for research and development in observing and modeling

a. *In situ observations*

There are numerous sources of in situ data that could help to address the science questions posed in section 2 of this paper. These include data rescue and recovery operations, augmentation of existing observing networks, and development of new networks, often in conjunction with focused field experiments. Each of these options is discussed in the following paragraphs.

Long-term monitoring and experimental hydrologic data are archived in a variety of forms and at diverse locations. There is a wealth of data on water and soils but fragmentation across agencies and archives has resulted in the underutilization of this information. In some cases, recovery of measurements made over long periods is a cost-effective form of investment that a government or institution could make for long-term environmental monitoring and change detection.

The decay of monitoring networks over the last 30 years due to political and fiscal instabilities has been substantial. For some hydrologic and climate variables less is known today than a few decades ago in terms of measurements. National and international agencies must take effective measures to reverse the trend in monitoring network losses.

There is a need for a series of workshops that could focus on strategies for carrying out particular data rescue operations. Participants should include digital archive specialists, institutional representatives, and end users. Funding and mission agencies need to provide incentives for individuals or groups to engage in cost-saving data recovery activities that will benefit the larger hydrologic community. A distributed information network could serve as the dissemination medium for the recovered data.

For a relatively low cost, existing observing networks could be augmented to provide valuable new in situ measurements. Technological advances in instrumentation allow the addition of new variables to the suite of standard measurements available at existing monitoring stations. Examples include addition of soil thermistors to measure soil temperature, devices to estimate soil water content, instruments to sense snow properties, and robust devices to measure surface moisture and energy fluxes. In many cases, real-time telemetry of both standard and new types of measurements may be technologically feasible and cost effective. Stream gauging can certainly be made more efficient and cheaper through telemetry. Water surface elevations and gradients can be monitored at a greater number of points along channels and within floodplains. This could greatly facilitate the measurement of floodwaves and improve our understanding of floods. Sediment and solute sampling can also be automated well beyond current levels.

Data users and providers need to work together in cost–benefit analysis of new and augmented observing systems (e.g., Showstack 1998). This is another instance where focused workshops with broad participation could be very helpful. The impact of expanded and extended measuring stations within each network needs to be assessed in terms of both scientific impact and operational benefit. Scientific impact can be measured relative to a set of critical science questions such as those posed in this paper. Operational benefit can be related to the disaster costs avoided through improved predictions and more advanced warning capabilities. Documentation of the economic, policy, and scientific value of open-release policies of organizations may motivate other national and international agencies to take similar steps. Finally, protocols and regulations for effective user access to data archives need to be established in clear terms.

It is often advantageous to simultaneously monitor several processes that are coupled to hydrologic systems. For example, data on diurnal variations in the temperature and humidity profiles of the atmospheric boundary layer and observations of conditions in the troposphere can provide important information for surface water and energy balance studies (see Fig. 4). Subsurface flow pathways can be better characterized if traditional hydrologic measurements are supplemented with observations of natural chemical tracers. Tracers can also be used to improve estimates of long-term sediment loading and to quantify sediment fluxes between floodplains and rivers. In all these examples, and in other similar cases, augmentation of traditional sampling programs can be a highly cost-effective way to obtain the data needed to address key science questions.

A final priority for in situ data collection is the development of focused validation datasets that can be used to evaluate new hydrologic theories, models, and remote sensing techniques. These datasets should be obtained from a variety of basins and regions characterized by different topography, climate, vegetation, and snow conditions (see Fig. 7). They should also be closely coordinated with related remote sensing experiments and ground truth studies, preferably under the auspices of international agencies and hydrologic initiatives (see discussion in the remote sensing section that follows). Validation datasets could fit within the continental-scale basin experiments of the Global Energy and Water Cycle Experiment (GEWEX). But they should also include smaller areas that can be monitored more intensively (WCRP 1997; NRC 1998).

Data provided by data recovery activities, existing and expanded observing networks, and other sources need to be properly archived, well organized, and readily available if they are to be of value to the user community. These objectives could greatly benefit from standardization. There is a pressing need for protocols and standards for systematically linking various hydrologic data archives. These should be devel-

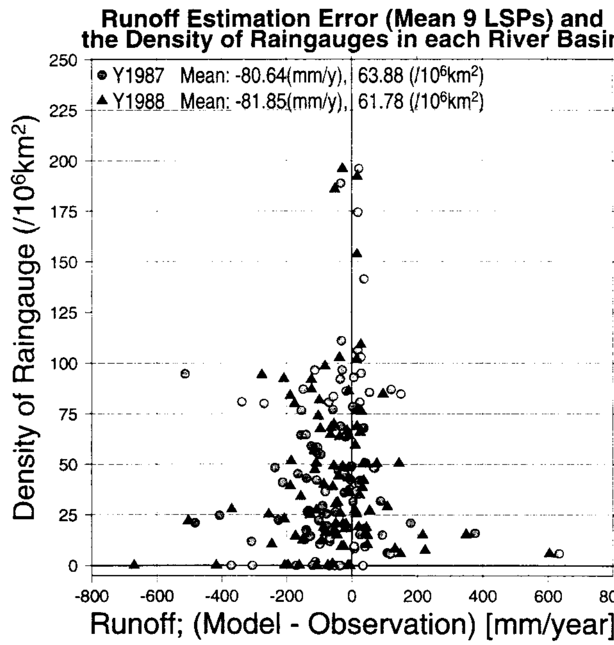

FIG. 7. The importance of high quality in situ data to hydrological modeling is indicated. Each of a number of different river basins is represented in the plot by two points: a circle for 1987 data, and a triangle for 1988 data. The abscissa represents "model error;" i.e., it represents the average runoff generated for the basin by nine land surface parameterizations (LSPs) minus the observed runoff there. The LSPs were forced with observed precipitation, radiation, and other atmospheric variables for 1987–88 as part of the Global Soil Wetness Project. The ordinate shows the density of rain gauges within the basin, a measure of the accuracy of the precipitation forcing used by the LSPs. The salient feature of the plot is the significant reduction in model error as the density of rain gauges increases. This suggests that much of the overall error in model runoff predictions may not be related to flaws in the model parameterizations but to an inadequate coverage of rain gauges (courtesy of T. Oki and cited in Dirmeyer 1997).

oped with broad participation by the hydrologic community, in cooperation with related communities in the earth and atmospheric sciences.

b. Remote sensing

Remotely sensed observations of land surface conditions from satellites and suborbital platforms (e.g., aircraft and balloons) provide synoptic high-resolution coverage that is unprecedented in the hydrologic sciences. The new information available from remote sensing technology may initiate important shifts in the conceptual basis for hydrology. Analogous shifts have already occurred in the atmospheric and oceanic sciences, where space-based observations have led to the reformulation of many fundamental disciplinary ideas. Hydrologists should be ready to embrace this special opportunity to rethink prevailing theories and approaches. The benefits for their discipline may be considerable.

For land surface hydrologic applications, the existing large amounts of multiangle visible and thermal spectral measurements have proven very valuable for hydrologic applications. These measurements have been used to estimate surface incident radiation, surface temperature, spectral albedo, land cover type, canopy structure features, and a number of other variables relevant to the derivation of energy and moisture fluxes at the land surface. Unfortunately, the atmosphere is a strong absorber and reflector of radiation in these frequency ranges, especially under cloud conditions. The error associated with atmospheric corrections under cloudy conditions precludes the use of visible and thermal spectral observations to retrieve surface fields that have relatively small and subtle impacts on the signal.

Fortunately, the atmosphere is relatively more transparent to surface emissions in the lower-frequency (longer wavelength) microwave region. This makes it more feasible to directly observe land surface variables of hydrologic interest. Polarized microwave emissivity is sensitive to near-surface soil moisture. An optimum soil moisture remote sensing system would be able to measure microwave radio brightness in spectral bands that are sensitive to soil moisture farther below the surface. The system would also provide measurements in spectral bands that are least affected by the atmosphere and moderate vegetation cover.

This is possible with low-frequency microwave radiation that is also used for telecommunications. Fortunately a few spectral bands are protected for radioastronomy. The band centered on 21-cm wavelength or 1.4 GHz (also known as the L band) is the lowest useful microwave frequency that can yield information on soil dielectric constant, which is related to soil water content (among other factors), down to a few centimeters. Design and deployment of missions to measure earth emission or reflection of radiation in this frequency is now among the unique opportunities for remote sensing in hydrology. There still remain some major questions that have yet to be adequately addressed, despite the fact that L-band microwave instruments have been developed and deployed for short periods of time on aircraft and spacecraft (see Fig. 8). There are, however, a number of important technical issues to be addressed. These include the design of space-borne antennae large enough to collect relatively weak microwave signals with sufficient fidelity, the design of retrieval algorithms that are robust under a variety of soil and vegetation conditions, coordination with spectral measurements at other frequencies, and the consideration of trade-offs between active radar and passive radiometry instruments.

Other land surface parameters can also be derived from remote sensing observations. These include topography, vegetation canopy structure, and mapping of inundation through side-looking radar and laser altimetry. Surface sediment concentrations in flowing water can also be recorded and interpreted to yield vertical concentration profiles or spatial patterns of mixing. Laser and radar altimeters offer the potential for measuring river stages and assessing floods.

In the current era, a successful remote sensing mission requires an end-to-end system optimization. This process starts with a clear set of scientific objectives that could apparently benefit from particular types of spectral data, as outlined earlier. A convincing case must be made that such data will, in fact, substantially improve scientific understanding and/or operational forecasting abilities. Once this case has been made, attention can turn to mission design. This includes an analysis of the maximum ground-level spatial resolution, minimum revisit frequency, maximum tolerable error in radio brightness of reflectivity, maximum off-nadir look angle, signal-to-noise ratio, and other characteristics of the mission under consideration. Trade-offs between passive and active remote sensing and synergistic use of multispectral (visible, thermal, and microwave) observations should be considered as part of this process.

Another important aspect of end-to-end optimization is simulations of space-borne measurements with numerical models and/or with suborbital prototype instruments. Important design issues that can be examined in this way include beamfilling, which occurs when heterogeneous small-scale surface properties yield a remotely sensed measurement that is not representative of regional conditions. It is advisable, as part of the design process, to test retrieval algorithms as well as instruments and mission design. These algorithms should be evaluated over a wide range of topographic, climate, soils, and vegetation conditions, in order to establish their range of applicability. Moreover, retrieval algorithms need to be integrated with compatible hydrologic models in order to provide "value added" data products that reveal the full implications of new remotely sensed observations.

The final stage of end-to-end optimization is the assessment of mission costs and the scientific and societal benefits. Benefits to be considered should include improved forecasting for hazard mitigation, and information that can help solve key agricultural, human health, water resources, and industrial policy problems. It should be apparent from the above discussion that end-to-end optimization requires a close working relationship between instrument specialists, spacecraft engineers, and applications scientists to properly translate scientific requirements into realistic systems. Such a dialogue should help to streamline the definition, development, and implementation process, resulting in cost reductions.

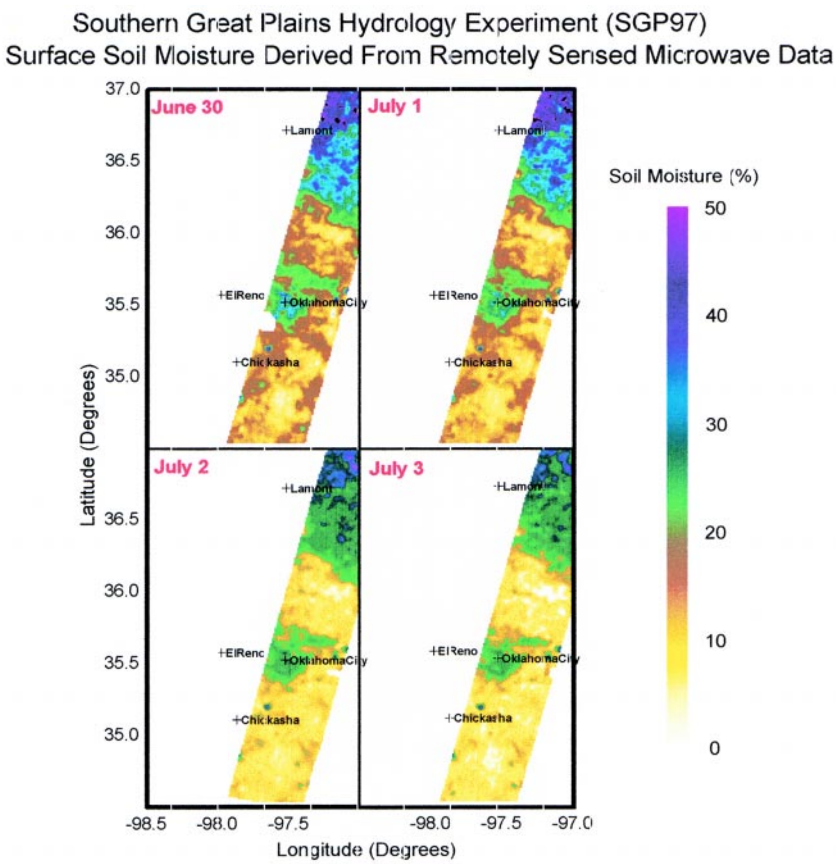

FIG. 8. Remote sensing technology can transcend many of the economical and logistical problems that limit the effectiveness of in situ measurement systems. An example of the potential use of remote sensing for hydrological research is shown above. During the Southern Great Plains 1997 Hydrology Experiment, the L-band Electronically Scanned Thinned Array Radiometer was deployed on a low-flying aircraft (Jackson et al. 1999). Daily mapping of surface brightness temperature over an area greater than 10 000 km^2 and a period on the order of a month was conducted. Sample images from two consecutive days in June show a large drop in brightness temperature at the top of the mapped region in response to the significant rainfall event that covered the area in the interim between samplings. Surface soil moisture fields may be inferred from such remote sensing observations with good accuracy. High costs would prohibit the estimation of spatial fields of soil moisture across large areas using in situ probes.

It is important to note that end-to-end optimization is relevant to analysis of existing as well as new remote sensing missions. The same assessment of multispectral synergy, retrieval algorithm performance, measurement and retrieval error budget calculations, value-added data production, and data quality control should be carried out with existing remote sensing measurements. In fact, the same framework also applies to ground-based technologies such as weather-sensing radar. In all of these cases, there is a need for careful evaluation of retrieval algorithms, errors, and potential benefits.

The ready availability of remote sensing information poses a number of specific challenges, both intellectual and organizational, to the hydrologic community, including the following.

1) Classic data-poor hydrologic models designed to function with (and calibrate with) sparse in situ observations of precipitation, stream discharge, and surface air micrometeorology will need to give way to new distributed hydrologic models that are forced with remotely sensed observations. More attention will need to be given to formulating models with pa-

rameters that can be directly measured, rather than calibrated.

2) Basin-scale and regional validation databases consisting of coordinated in situ and remote sensing data collection programs will need to be established in order to properly evaluate instruments and retrieval algorithms. Such validation data should provide the basis for assigning error statistics to remote sensing observations. The validation sites should be located in regions with different topography, climate, vegetation, and snow conditions.
3) Hydrologists need to evolve from passive recipients of limited remote sensing observations to acting as a unified scientific community that is engaged in supporting the definition, design, and implementation of suborbital and space-borne missions. The key to fulfilling this challenge is a clear demonstration of the positive impact of existing and emerging observation streams on the major scientific objectives and questions.

Other challenges will undoubtedly arise as new data types begin to have impact on hydrologic theory and practice.

c. Data assimilation

Remote sensing technology provides many types of spectral data that are related to land surface variables of interest to hyrologists. However, very little of this information is available in a form that can be used directly for hydrologic purposes. Various types of data retrieval algorithms are needed to convert spectral data into variables of hydrologic value. In fact, a similar situation exists for some types of in situ information, such as data used to infer soil hydraulic properties. Here again, properties of hydrologic interest must be inferred from available measurements, with the aid of retrieval or data processing algorithms.

The simplest data retrieval algorithms are based on observed correlations between spectral measurements and hydrologic variables. Such algorithms may not provide data that are compatible with fundamental physical principles such as conservation of mass, momentum, and energy. Moreover, they may not be able to extend available measurements over the regions and time periods of interest in a particular hydrologic application. An important example is the use of soil moisture retrieval algorithms that process passive microwave radiance measurements. These algorithms provide information on soil moisture only in the top few centimeters of the column. An ideal data processing algorithm would be able to extend such measurements farther down the soil column by accounting for time–space relations implicit in the vertical movement of soil water.

Meteorology and oceanography have extensively developed the concept of "adding value" to data, especially remote sensing data, by combining measurements with the predictions of specially selected models. This process, which is commonly known as data assimilation, is an extension of standard data retrieval techniques. Data assimilation is distinguished by its reliance on spatially distributed hydrologic models that incorporate physical principles such as mass, momentum, and energy conservation. These principles act as strong constraints on the estimates produced by the assimilation algorithm.

It is important to note, however, that data assimilation algorithms are data driven rather than model driven. This means that data assimilation models are designed specifically to aid in data processing rather than model simulation (and calibration). The variables in a data assimilation model must include the measured spectral data and must be integrated with other retrieval algorithms required to translate raw signals into useful hydrologic information. They also must be computationally efficient, since they are typically integrated into a larger set of processing and retrieval algorithms (e.g., atmospheric).

One of the primary purposes of data assimilation is to produce data products that are directly useful for hydrologic analyses. Such products need to be carefully designed so they meet the needs of potential users. Issues to be considered include the resolution and spatial configuration of the data product, quantitative measures of data product reliability, quality control issues (e.g., dealing with "outliers"), and sensitivity of the data product to "hidden" model properties. All of these issues are important but most have been addressed, at least to some degree, in similar contexts by oceanographers and meteorologists. The challenge for hydrologists is to develop data assimilation algorithms that benefit from previous work in other disciplines while meeting the special needs of hydrologic science and practice.

Certain aspects of hydrologic processes and data sources are particularly compatible with the methods and objectives of data assimilation. First, hydrologic systems often function over a wide range of timescales. For example, vegetation canopy structure varies on the scales of seasons, while surface temperature and moisture vary diurnally. Data assimilation algorithms that need to simultaneously estimate canopy interference and surface emission may utilize high-frequency radiance measurements but keep the canopy parameters as temporally invariant over weeks or months. The degrees of freedom needed to carry out the estimation process are thus reduced significantly.

A second incentive for the use of data assimilation in hydrologic remote sensing applications is that auxiliary data from in situ observations may often provide important information on factors contributing to the remotely sensed signal. For example, a data assimilation algorithm may be used to merge soil texture measurements, surface micrometeorology, and in situ land use data with remote sensing measurements.

Finally, the data assimilation framework may be used to analyze the value of various observing systems through the so-called data-denial experiments. In these experiments the value of a particular data source can be quantified in terms of the effect it has on estimates of a particular hydrologic variable.

It is worth noting that the NRC (1998) report on the GEWEX Continental International Projects recognizes the critical importance of developing and implementing land data assimilation systems. Experiences with land data assimilation systems have shown that estimates of land surface states can be quite sensitive to errors in the estimation of cloud cover and precipitation. In turn, some of the errors in cloud and precipitation amounts in atmospheric data assimilation systems are due to errors in surface flux estimation. Thus improvements in coupling of land and atmosphere components of models and the boundary layer are necessary for the implementation of refined land and atmosphere data assimilation systems.

A number of important research and operational issues need to be resolved if data assimilation is to achieve its potential for "adding value" to hydrologic measurements. Statistical techniques for describing multiscale spatial heterogeneity need to be incorporated into algorithms that account explicitly for the multiresolution nature of different but complementary hydrologic measurements (such as rain gauges, ground-based radar, and satellite radiance measurements of precipitation). Computationally efficient sequential assimilation techniques that are capable of adequately characterizing multiscale temporal dynamics should also be investigated for applications to hydrologic remote sensing.

Classic hydrologic models that have been optimized for use with sparse in situ observations such as precipitation accumulation and streamflow are inadequate for extension to work with remote sensing data. Models and model components for land surface processes need to be developed following criteria for parsimony and observability. Procedures for their rigorous validation need to be defined. It should be recognized that land surface hydrology models for simulation and for assimilation applications may have significantly different requirements/characteristics.

Finally, the importance of modeling studies that do not employ data assimilation must also be stressed. Such free-running models (e.g., coupled land–atmosphere models) have prognostic variables that vary in response to the modeled physics. This makes it possible to carry out sensitivity studies that help isolate and characterize physical controls over hydrological variability. Realistic model physics and coupling behavior is, of course, critical to the credibility of such sensitivity analyses. Many of the priority science questions outlined in section 2 relate to increasing the realism of hydrological models, whether they are used for data assimilation, sensitivity analysis, or hydrologic forecasting.

4. Recommendations: A second international hydrological decade (2d IHD)

The authors believe that the discipline of hydrology is intellectually and technologically ready to address the science issues outlined above. In this section, we propose a scientific initiative—the Second International Hydrological Decade—that would serve to enable and facilitate the needed research.

This infrastructure is best introduced by describing the relevant precursor, the First International Hydrological Decade (1st IHD). During the 1st IHD, which covered the years 1965–74, a series of international workshops on the current and future problems in various subdisciplines of hydrology was organized, and reports of these activities were published by the United Nations Educational, Scientific, and Cultural Organization (UNESCO 1972, 1974a–e). The more enduring legacy of the 1st IHD is the international data collection activity that for the first time provided worldwide sharing of observations. The 1st IHD had major impacts on the emergence and maturation of the hydrologic sciences.

The atmosphere of change and excitement in hydrology today is reminiscent of the period leading up to the 1st IHD. However, almost a quarter of a century has passed, with an associated shift in the way the science is approached. First, hydrologists now widely recognize that land surface hydrologic processes are closely coupled with the subsurface and the overlying atmosphere. This realization is reflected in the science questions of section 2, and it has important implications for both modeling and observing strategies, as discussed in section 3. A second distinguishing feature of modern land surface hydrology is that the global or large-scale approach is often the starting point, and the challenge is to characterize regional or smaller-scale features. The river basin is no longer the exclusive unit of study. A third distinguishing feature is, as discussed in section 1, the emergence of new technology and substantial amounts of data in nontraditional forms. Hydrologists must determine how to optimize their use of these potentially highly valuable data.

The recent changes in approach must be considered in the context of current critical issues in hydrology. In a recent address, the World Meteorological Organization (WMO) Secretary-General Dr. G. Obasi posed two contemporary challenges to the hydrology and water resources community: 1) reverse declining trends in the development of hydrologic observing systems, and 2) reduce prediction and analysis uncertainty so that managers and policy makers can more effectively use the results of scientific and technical activities (Obasi 1999). The first challenge is principally dependent upon international cooperation among national and regional agencies. Specific issues to address include capacity building, technology transfer, telecommunications and archiving technologies, and protocols. The second challenge falls on the shoulders of the research community. This community should develop scientific tools to make effective use of the data provided by new observing networks and systems. Furthermore, they should strive to reduce uncertainties that limit the usefulness of their products to the water resources management and policy making communities.

The core purpose of the 2d IHD is to address these two challenges. We now have the sensing and data processing technologies needed to characterize the global distribution and movement of water and energy, across a wide range of scales. Moreover, these technologies provide information at accuracies and resolutions hitherto unimaginable. The set of new science questions stimulated by recent technological developments is also global in scope. Answers to these questions lie at the interface of hydrology and climate and hold the promise of great societal benefits. The tools and science questions are at hand and the 2d IHD is the medium for realizing their potential.

Data collection efforts would be directed toward meeting the agenda's goals. These efforts would build on ongoing international programs that, similar to the 1st IHD, are directed toward the expansion of observing networks and the international exchange of data. The World Hydrological Cycle Observing System (WHYCOS) and Global Climate Observing System (GCOS) are well-designed and comprehensive international programs for expanding observing networks, capacity building, technology transfer, and data exchange (WMO 1995, 1998). The implementation of these programs is a challenge for the WMO and it represents substantial international cooperation efforts. As mentioned earlier, data rescue efforts based on existing but nonarchived measurements are also important sources of information. The World Climate Research Program (WCRP) reports two examples of initiatives to recover existing observations. The Data Rescue program in Africa and North and Central America, and the Archival Climate History Survey in Europe are designed to rescue and preserve climate data and their associated metadata (WCRP 1997). The 2d IHD may similarly focus on climate and hydrological data rescue and recovery for hydroclimatology studies dealing with low-frequency variability or nonstationarity (change). The activity may be expanded to include valuable experimental basin records, water quality, soil and land use surveys, and data from special or nonoperational observation missions. WHYCOS, GCOS, data rescue, and associated programs with regional or specialized emphasis will certainly form the backbone of future advances in reducing hydrological hazards and increasing freshwater availability for growing populations.

This paper outlines a proposed scientific agenda for the 2d IHD, an agenda that could drive land surface hydrology research during the next 10 years. The proposed agenda is open to debate—our intention is to put our proposals "on the table" and thereby stimulate discussion in the larger community. A final form of this agenda, modified as necessary to reflect the concerns of the hydrological community at large, must still be established. This final agenda would give the 2d IHD focus and would provide guidance for the allocation of limited research and observing system resources.

The burden of making the agreements and protocols that will launch the 2d IHD falls on national and international institutions and agencies that deal with scientific research and cooperation, water resources, and natural hazards. The agenda for land surface hydrology proposed here demonstrates the readiness of the research community to take the initiative for advancing the discipline. Hydrologists can and should take the lead in developing the scientific knowledge required to address contemporary global environmental issues such as food security, human health, and economic development. A focused research agenda for a 2d IHD, whatever its final form, should give hydrology the direction it needs to address the critical science and water resource problems of the next century. This is an opportunity that will provide great benefits, both for the discipline and for society as a whole.

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