CONSORTIUM OF UNIVERSITIES FOR THE ADVANCEMENT OF HYDROLOGIC SCIENCE, INC.

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CUAHSI

universities allied for water research

A VISION FOR HYDROLOGIC SCIENCE RESEARCH

A Report to the Consortium of Universities
for the Advancement of Hydrologic Sciences, Inc.

by

the Hydrologic Science Standing Committee

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INTRODUCTION

Hydrologic science deals with the "occurrence, distribution, circulation and properties of water on the Earth. It is clearly a multidisciplinary science as water is important to and affected by physical, chemical and biological processes within all the components of the Earth system: the atmosphere, glaciers and ice sheets, solid Earth, rivers, lakes and oceans (NRC [1991])". Hydrologic science also deals in the most fundamental ways with human needs and activities. The scientific community has produced convincing evidence that, because of the effects of human civilization, Earth is experiencing environmental changes of an unprecedented magnitude. In the next hundred years, most areas will likely undergo major changes in temperature, and significant changes in regional precipitation are possible. Shifts in the water cycle will be perhaps the single most significant aspect of these changes. These changes will have enormous impacts on human populations. Are we in a position to predict the nature of these shifts and their effect on the hydrologic cycle? At the present time, the answer clearly is "no" (Phillips [2002]).

If we are to successfully adapt to changes and uncertainty in our freshwater resources, we need to improve our understanding of, and ability to characterize and predict, the storage, movement, and transformations of water in natural and impacted conditions. The principal science objective underlying CUAHSI infrastructure proposals is to develop a predictive understanding of storage, fluxes, and transformation of water, sediment, and associated chemical and microbiological constituents.

Some of the most challenging problems associated with developing a predictive understanding of hydrologic processes concern interfaces and transition zones, such as the land-atmosphere interface, the water table, the interface between groundwater and surface water flow systems, and the transition zone between hillslopes and stream channels. These interfaces challenge our process understanding, our measurement capabilities, and our ability to model coupled hydrologic processes. This theme is described in Section 1 with special emphasis on the connections between interfaces in the hydrologic cycle and their links to human impact on water resource systems.

Three additional themes closely intertwined with the core science objective are: (1) the role of scale in hydrologic storage, fluxes, and transformation, (2) the linkage between ecosystems and hydrologic cycle, and (3) hydrologic prediction. These themes are elaborated in Sections 2-4. In Section 5, we describe the linkages between water management and hydrologic science.

1. STORAGE, FLUXES, AND TRANSFORMATIONS IN THE HYDROLOGIC CYCLE

As water cycles at Earth's surface, it undergoes numerous phase changes between solid, liquid, and gas, while it flows through and is stored in a wide variety of media. In the atmosphere it mixes as a gas, and coalesces in clouds. At the land surface it perches above the land in lakes, rivers, wetlands, and glaciers. In the near surface it hangs in the void space of soil and rocks, and fills the cells, xylem, and stomata of vegetation. Deeper from the surface it completely fills the pore spaces and cracks of rocks and sediments. The physical, dynamical, and chemical processes that control the movement and storage of water throughout these media are incredibly varied. Water is subject to forces of gravity, pressure, surface tension, and osmosis, and it is heated by radiation and conduction. It responds with viscous and turbulent flows, diffusion, and numerous phase changes.

To develop a predictive understanding of these processes, it is necessary to develop the analytical and measurement tools to quantify all components of the hydrologic cycle. Quantification of hydrologic budgets and transport of sediment, microbes, and chemicals across hydrologic boundaries requires knowledge of water fluxes across these boundaries. The boundaries of interest are the:

1. atmosphere-land surface interface,
2. land surface-groundwater interface,
3. groundwater-surface water interface, and
4. land surface-surface water interface.

Our process understanding and ability to quantitatively predict water fluxes in isolated media, away from boundaries, is generally better than at the interfaces of these boundaries, where the characteristic physical processes change and parameterizations are required to express their coupling. But it is generally at these interfaces that we are most interested in, and in many cases define, hydrologic fluxes. For some fluxes, our heuristic understanding (in a sense, our progress) is expressed in terms of which "side" of the interface holds the processes that rate-limits the magnitude of flux across the interface. For other fluxes understanding is expressed in terms of which sub-processes on the rate-limiting side are controlling. And for others it is expressed in terms of processes at the interface itself. In general, the rate-limiting process, where there is one, changes with ambient conditions (geographically, seasonally, and even diurnally). Taking soil evaporation at the atmosphere-land surface interface as an example, the limiting factor could be the net flux through the soil (vs. turbulent transport in the atmosphere), and within the controlling sub-process could be vapor or liquid diffusion. Identifying such rate-limiting processes lends itself not only to a basic process understanding , but also leads to parameterizations required to couple relevant processes in predictive and diagnostic models.

Identifying rate-limiting processes can lead not only to a basic understanding of process, but also to improved models for prediction and methods for estimation. For example, knowing under which precipitation/soil conditions runoff generation becomes infiltration-limited allows us to predict the potential impact of higher or lower intensity rains under a changed climate. If the runoff generation is not infiltration-limited, it is likely that changing rainfall intensity will have little to no impact. Likewise it points to the critical soil parameters that need to be measured for estimation and prediction. For example, porosity and depth to water table matter more for storage-limited runoff, while hydraulic conductivity matters more for infiltration-excess runoff.

As scale increases from the few centimeters over which Darcy fluxes are defined to the hundreds of kilometers of large watersheds and aquifers, more and more of these interfaces and processes are included, and it becomes more difficult to identify controlling processes. Large-scale observation networks covering groundwater, vadose zone, and atmosphere processes, in conjunction with coupled process models, could lead to new insights into what really controls water balance at basin scales. It is entirely possible that what we assume to control the balance, based on point-scale/stand-alone process understanding, may be incorrect. Identifying the controlling, or rate-limiting factors is necessary for understanding, prediction (including sensitivity analysis of land-cover land-use changes and climate change), and estimation techniques.

The linkage between storage, fluxes, and transformations in the hydrologic cycle and water resource management problems is complex. Human activities may immediately affect one component of the hydrologic cycle, and additionally have long-term impacts on other components of the hydrologic cycle. An example is sewage leaking into the ground from a septic tank (an anthropogenic activity), which then slowly moves through an aquifer under natural flow conditions into the surface water system, contaminating a stream and potentially having an impact on drinking water quality and stream biota. In order to adequately assess the water supply and the movement of chemicals, microorganisms, and sediment through the complete hydrologic cycle, these processes must be evaluated on a watershed-scale basis. Our ability to predict hydrologic change and associated water quality over large distances and times (kilometers, years) within the complete hydrologic cycle has been limited by the scope of the typical university-based research grant, in that the processes cannot be evaluated for long periods of time over large scales due to the prohibitive costs of such studies.

In the following three sub-sections, examples of scientific problem areas linked to hydrologic boundaries are presented and connected to water resource management problems. The land-atmosphere interface is examined in Section 1.1 in connection with problems related to land-atmosphere interactions. The land surface-groundwater and groundwater-surface water interfaces are discussed jointly in Section 1.2 in connection with groundwater recharge and discharge. Problems of sediment storage and transport are discussed in Section 1.3 in connection with the land surface-surface water interface.

1.1 LAND-ATMOSPHERE INTERACTIONS

The land surface exerts a profound influence on weather and climate. Some of the effects of the land surface on weather and climate are associated with the natural heterogeneity of Earth's surface, especially contrasts in topography and land-ocean boundaries. Other effects are associated with anthropogenic modifications of the land surface, especially urbanization and conversion of forest land, desert, and wetlands to agriculture. In addition to these relatively static processes, the rapidly varying moisture state of the land surface can have a significant impact on weather through its control of evaporative fluxes to the atmosphere. Spatial contrasts in the land surface are translated into heterogeneities in the precipitation forcing that drives the surface and subsurface hydrologic cycle. For many of the water resources management problems and environmental change problems faced by society, characterization and quantification of these heterogeneities is either the crux of the problem or a pre-condition to solving the problem. Research in land-atmosphere interactions is needed to examine the impact of heterogeneous land surface properties on the atmospheric branch of the hydrologic cycle.

The effects of mountains on weather and climate range from modulations of the global-scale Rossby waves that determine the continental-scale structure of weather systems to the local amplification of precipitation through orographic precipitation mechanisms. The role of mountains in determining the precipitation-rich and the precipitation-poor parts of the globe is of fundamental importance for water resources management. Equally important is the role of mountains in determining the regions subject to hazards associated with extremes of precipitation. The global extremes of precipitation on both the high end (the Khasi Hills of India, La Reunion, and Mt. Waialeale on the island of Kauai, for example) and the low end (Atacama Desert of Chile) are tied to orographic precipitation mechanisms. Mountains are one of the major sources of heterogeneities of the land surface hydrologic cycle and these heterogeneities are propagated through the hydrologic cycle. The physical mechanisms by which mountains determine the spatial and temporal distribution of precipitation are not understood well enough to make informed decisions on efficient management of water resource systems. Understanding is hampered by the absence of an experimental base for scientific advances. The Mesocale Alpine Program, which was carried out in northern Italy in 1999, has provided a successful example of the experimental framework that can address this problem.

Coastal regions are among the most densely populated areas of the world. They are subject to chronic problems of freshwater availability and environmental hazards that are characterized by sharp land-ocean gradients. These gradients are closely linked to contrasts in precipitation distribution strongly influenced by the land-sea boundary.

Land breeze and sea breeze circulation systems are an important determinant of the spatial, seasonal, and diurnal distribution of precipitation in coastal regions. Land-falling tropical cyclones are a major flood hazard and an important element of the precipitation distribution in many coastal regions. Tropical storms over open ocean can persist for days in near steady state condition. Once tropical storms interact with land, they typically weaken (as reflected in decreased wind speeds and pressure gradients) due to frictional effects and diminished latent heat supply to the storm. The behavior of tropical storms over open ocean still contains many mysteries, but it is far better understood than their behavior over land. Management of water resources in coastal regions is hampered by the difficulties in characterizing the influence of the land-ocean boundary on precipitation distribution.

There is growing recognition that anthropogenic changes to the land surface can result in changes to regional climate. Of particular importance to water resources management are changes in precipitation distribution. Experimental and numerical model studies of the effects of deforestation in the Amazon basin on regional climate have pointed to a number of difficult scientific problems that have important consequences for coupled land and water resource management. Impacts of deforestation on regional climate are tied not only to the extent of deforestation, but also to the pattern of deforestation. The effects of a 50 km by 50 km region of deforestation would be different from the effects of a 250 km by 10 km region of deforestation or 100 deforested patches of 25 km^2 embedded in a 10,000 km^2 region. Accurate characterization of land surface composition over a broad range of scales is crucial for assessing and managing the impacts of land transformation on regional climate. The impacts of land surface change are closely linked to the changing fluxes of both latent and sensible heat. The coupling of water and energy budgets is central to assessments of changing regional climate. The difficulty measuring evaporation is one of the key problems of addressing the impacts of anthropogenic changes to the land surface on regional climate.

The Metromex experiment in St. Louis during the early 1970s demonstrated the influence of the “urban heat island” on regional precipitation distribution. At the time some of the conclusions were quite surprising. One surprise was that urbanization exerted a significant influence on regional precipitation distribution. The effects were most pronounced during the warm season and had the greatest impact on systems of thunderstorms. Rainfall amplification did not occur in St. Louis proper but in rural areas “downwind” of the city. Urbanization has become an increasingly important issue both in the United States and globally, but Metromex continues to provide much of the scientific base for assessing impacts of the urban heat island on regional weather and climate. Urbanization in the corridor from Washington D.C. to Boston, Massachusetts has created one of the most complex precipitation regimes in the United States. The combination of urban heat island effects, land-sea breeze circulation systems, and orographic precipitation mechanisms is recognized by every weather forecaster in the region as part of the mix that affects precipitation distribution. How this mix works is poorly understood relative to the water resource management and hazard assessment problems at stake. Metromex provides a clear guide to the experimental approach needed for addressing the impacts of urbanization on regional weather and climate.

The time-varying moisture state of the surface provides a dynamic control of regional weather and climate. Soil moisture anomalies have been examined as one of the ingredients of the period of heavy rainfall resulting in the Mississippi flood of 1993. A direct link between soil moisture anomalies and precipitation distribution was established by the Illinois State Water Survey for a storm that produced record rainfall (425 mm in less than 24 hours) in the upper Midwest. Heavy rainfall on 17-18 July 1996 in Illinois can be linked to soil moisture anomalies in Iowa produced by heavy rainfall on the preceding day. An important lesson from these analyses is that the impact of soil moisture on weather and climate is tied to the coupled fluxes of water and energy to the atmosphere. A principal influence of soil moisture anomalies on weather and climate is through thermodynamic modifications of the atmosphere that promote storm development and intensification. As with problems related to deforestation, the pattern of soil moisture anomalies plays an important role in assessing impacts of these anomalies on regional weather and climate. Characterization and monitoring of soil moisture and vegetation over a wide range of scales is a central problem in assessing the role of the changing moisture state of the surface on regional weather and climate.

Climate variability over decadal to millennial time scales represents one of the greatest challenges for water resources management. Water systems must be robust to climate variability over these time scales, yet the basic scientific understanding of climate variability over these time scales is poor. Emerging evidence points to the importance of land surface processes for climate variability, with both anthropogenic and natural processes playing a significant role. At the extreme end of the hydrologic spectrum, the processes responsible for desertification may include feedback effects associated with human activities.

Evaporation is one of the principal means of communication between the land surface and atmosphere. It is also one of the most difficult elements of the hydrologic cycle to measure. Advances in assessing the impacts of land surface heterogeneities on regional weather and climate require major strides in measurement of evaporation.

1.2 GROUNDWATER RECHARGE AND DISCHARGE

Because of the high quality, constant temperature, and relatively low variability of groundwater, its recharge and discharge near the surface is critical to both humans and ecosystems. Quantitative information concerning the spatial and temporal distribution of these fluxes, under existing conditions or conditions of changed climate and/or land use and cover, is important to a number of issues including water supply development, regulation of point and non-point contamination of surface waters, aquatic habitat assessment, establishment of instream flow requirements, and assessment of pumping impacts on aquatic ecosystem. The need for this information can only increase with increases in population and its associated impacts on aquatic systems. Particular attention in problems of groundwater recharge and discharge is focused on the unsaturated zone and the hyporheic zone.

The hyporheic zone is the region of sediment immediately surrounding and beneath a stream where the groundwater and surface water environments come into contact. The size of the hyporheic zone can vary with the types of streambed and bank sediments, the slope of the streambed, and the hydraulic gradients in the surrounding groundwater environment. Hyporheic exchange affects the chemical properties of both surface water and shallow groundwater, and has been shown to have pronounced ecological consequences. Storage within the hyporheic zone can potentially dampen the hydrologic and biogeochemical (including pollutant) consequences of floods. Groundwater exchange into streams can lessen the impact of droughts, at least in the short term. The hyporheic zone can serve as a source of nutrients and microorganisms to the stream and to the shallow subsurface, can play an important role in mitigation of surface-water pollution, and is a region of active hydrobiogeochemical processes, with gradients in temperature, oxygen content, nutrient concentrations, and microbial ecology. Because the hyporheic zone is by definition an interface between surface and subsurface water environments, it is one of the least understood portions of the hydrologic cycle, and requires new approaches at the boundaries of surface and subsurface hydrology.

The problem of understanding and predicting the spatial and temporal distribution of groundwater recharge and discharge is an important challenge to the science of hydrology. These fluxes are the integrated result of virtually all other hydrologic processes, and their variation in space and time appears to depend on numerous local and regional conditions. Up to now, interest in the latter has dominated, and predictive efforts have largely been empirically driven. The challenge to the science is to show that significant improvement in predictive capacity can result from scientific efforts focused on both individual processes related to recharge and discharge and their couplings.

The key processes and factors that potentially control the space-time pattern of groundwater recharge and discharge are generally well known. The processes include precipitation, infiltration, evapotranspiration, percolation and capillary rise through the unsaturated zone, and groundwater flow divergence. The factors affecting these processes include topography, soils, vegetation, land use, subsurface geology, and climate. In spite of this general understanding, however, we have very limited ability to predict groundwater recharge and discharge in specific watersheds. Reliable tools and methodologies simply do not exist to assess aquifer recharge at the typical watershed scale (10-1000 km^2) or at the watershed modeling grid scale (1-10 km^2).

A formidable challenge for quantifying fluxes across the land surface-groundwater (recharge) interface and groundwater-surface water (discharge) interface is characterizing the spatial heterogeneity of the subsurface properties controlling these fluxes.

A combination of large-scale remote sensing coupled with land-based and subsurface instrumentation and appropriate large-scale tracer tests is required to quantify these components of the hydrologic budget on the watershed scale. An example of a promising technology for locating discharge areas from the subsurface to surface water bodies is infrared imaging. However, of infrared radar flyovers are normally prohibitively expensive and not accessible to the average university researcher.

Few studies have had sufficient data to develop methodologies to incorporate spatial and temporal variation of recharge. Key elements currently limiting the development of recharge estimation are: (1) limited field comparison and testing of available and emerging recharge estimation methodologies; (2) limited ability to scale point measurements of recharge up to the modeling scale, and lack of validation/testing data; and (3) limited testing of combining water balance components measured at differing scales, i.e., rain gauges, radar estimation of precipitation, satellite-derived estimates of evapotranspiration, and watershed scale measures of runoff into accurate measures of aquifer recharge.

The impacts of the proposed watershed scale research go directly to the heart of water resource issues. Currently, few tools exist to balance the often-conflicting objectives of water resource extraction with protection of water resources for other uses such as in-stream flows or endangered species. With the development of efficient recharge estimation tools for climatic regions ranging from humid to arid, public debate over the allocation and use of water resources will have a solid foundation of rigorously tested tools and will have the methodologies with which to make water management decisions. Water resource planners and public policy makers will be able, in quantitative terms, to assess the impacts of future climate change on groundwater availability, to quantify the impacts of groundwater extraction on stream flows and to better understand the linkages between groundwater and surface water across a wide spectrum of hydroclimatological regions.

Problems of groundwater recharge and discharge are particularly difficult in karst regions. Karst covers approximately a quarter of Earth's land surface and provides potable water to a quarter of the world's population. In these regions, the distinction between ground and surface water is blurred because of rapid recharge through sinkholes and high transmissivity of the conduit systems. This link between surface and ground water makes land use changes critical for both surface and ground water quality. In addition to providing water for human consumption, karst aquifers also support numerous endemic and endangered species (snails to manatee) that rely on discharge from karst springs. These aquifers also support chemosynthetic microbial communities that may be the base of the food web and might also provide habitats for novel microbial species. In spite of rapid flow through karst aquifers, some preliminary water quality monitoring indicates chemical contamination and ecological disturbance has been increasing on decadal time scales. Water quality and physical hydrogeology are thus critical issues for karst aquifers. Regardless of their significance, little is known of contaminant pathways through the aquifers, flow paths to springs, chemical behavior of contaminants, or the ultimate effect of contamination on endemic flora and fauna. On a regional scale, karst aquifers can be approached by traditional hydrogeologic methods (as equivalent to porous media), but on a local scale, the complex nature of karst that results from the range of porosities and permeabilities requires alternate approaches.

1.3 SEDIMENT STORAGE AND TRANSPORT

A significant effect of the interaction between humans and the environment involves the movement of sediment from land into streams and within the stream system. Elevated transport of sediment into surface water bodies arises from agricultural practices, deforestation, and construction activities. In addition, flash flooding caused by increased land-surface impervious area can give rise to instream erosion, thereby contributing to the sediment export load from a watershed.

Soil erosion is well understood and can be reasonably well quantified. But because the transport of eroded soil is highly intermittent, it is much less well understood and poorly quantified. Of particular concern is the transport of fine-grained sediments, which accounts for most of the contamination. Restoration of water quality and ecosystem function in the Chesapeake Bay, for example, has focused on reduction of agricultural contaminants mobilized by soil erosion. Development of remediation strategies, however, has been plagued by uncertainties about transport and storage of sediment-associated contaminants, especially those associated with fine-grained sediment. It remains difficult to determine whether a soil particle eroded from a farm in Pennsylvania will arrive in the Chesapeake Bay within two weeks, two years, two centuries, or two millenia. The answer to this problem has major implications for development of strategies for efficient management of freshwater resources.

A challenge facing researchers today is quantification of sediment budgets on a watershed scale, like the drainage of Chesapeake Bay, so that the impact of sediment transport can be assessed. This type of activity is needed to document the effects of anthropogenic perturbations giving rise to sediment transport versus natural effects that would be expected to contribute to the process. An example type of study that could be used to distinguish anthropogenic effects versus natural effects would be a paired watershed study of various types of disturbed versus undisturbed watersheds in similar geologic and climatic environments, where the transport of sediment and sediment budget would be quantified over the long term.

There are numerous examples of deleterious effects of sedimentation on surface water systems in addition to those furnished by the Chesapeake Bay. One example is fish spawning areas composed of gravel where sediment clogging the gravel can kill embryos in fish eggs by depriving them of oxygen and reduce the flux exchange between groundwater and surface water systems. A second example is the growing problem in the United States of sedimentation of many multi-purpose reservoirs that are part of our aging water management infrastructure. While sedimentation is reducing the useful life and water storage capability of these structures, management decisions must be made as to whether to restore the reservoirs to their former water volume, and if so, what to do with the dredged sediment.

Another issue with sediment transport is the co-transport of chemicals (e.g., PCBs, phosphorous) sorbed to moving sediment particles that would not otherwise be present in the water column due to their chemical properties. This type of coupled process has significant implications for water quality management, because moving sediment can introduce chemicals into the water system that would otherwise be bound to the land. Water quality is affected by a combination of hydrologic, geologic, chemical, and biological processes. Integrated research accounts for the coupling of these factors and thus can accurately describe the chemical transformations that determine water quality.

Storage and transport of sediment in stream channels also plays a fundamental role in problems related to the structural properties of channel floodplain systems. Although river channel/floodplain systems are frequently examined from the perspective of equilibrium theory, many river systems throughout the world are in a disturbed or disequilibrium condition owing to altered flow regimes and sediment supply resulting from human activities. Implications for society are often profound but patterns of response in many cases are poorly understood. Consequently there is a need for more comprehensive understanding of characteristic spatial and temporal patterns of channel/floodplain system response to anthropogenic disturbance.

Public agencies and private groups presently are carrying out a second generation of river projects in the United States attempting to improve riverine conditions by returning them to a more natural condition. While the 20th century was replete with river projects seeking to tame and convert rivers for human uses, widespread efforts are underway to make the 21st century an era of returning rivers back to natural functioning. The need for such efforts stems from the well-documented loss of in-channel and streamside habitat, extensive river regulation, increasing flood risks and flood damages, changing societal attitudes, and the poor water quality of American rivers with ~50% non-fishable and non-swimmable. However, limited theory and data are available to guide the current efforts, which results in risky experiments yielding little or no basis for scientific advancement. In many cases, these experiments result in trade-offs in which hypothetical gains offset the destruction of well-functioning natural areas. Furthermore, larger scale integrated watershed management is rarely considered in localized project designs. If the science of river restoration and rehabilitation is not pursued aggressively, it is highly likely that the era of well-intentioned projects will merely serve as an efficient mechanism for further destruction of the environment.

2. SCALING OF HYDROLOGIC PROCESSES

Scaling of hydrologic processes deals with the seemingly arcane question of how hydrologic variables such as soil moisture, precipitation, and streamflow depend on averaging in space and time. Questions of scaling, however, are of fundamental importance for advances in water resources management and assessment of environmental change, because they are at the heart of our capability to monitor hydrologic systems. Measurements of hydrologic processes are invariably tied to particular time and space scales and these scales may not be directly appropriate for addressing water resource applications. "Scaling laws" provide the scientific foundation upon which relevant information in measurements of hydrologic processes can be generated at the appropriate time and space scales to resolve water management problems. Research on scaling of hydrologic processes would be a high priority to the water resources community solely from the perspective of addressing methodological issues dealing with hydrologic measurement. Research on scaling of hydrologic processes has also been a productive avenue for uncovering fundamental properties of hydrologic systems. Advances in understanding scaling properties of hydrologic processes will be central to the future of hydrologic science and to resolving problems of water resource management and assessment of environmental change.

The problems associated with defining and measuring soil moisture illustrate some of the fundamental scaling problems encountered in hydrology. Soil moisture is typically defined as the volume of water in a given volume of the subsurface. The properties of soil moisture depend strongly on whether the volume scale is 0.001 m^3, 1 m^3 or 1000 m^3. There is a minimum scale over which one can meaningfully consider this volumetric soil moisture content. That scale, which is difficult to determine, is certainly larger than the scale of individual pores of the soil matrix. As the volume averaging scale becomes small, the physics of pore scale fluid flow play an increasingly important role in our representation of soil moisture. As the volume averaging scale increases, our representation of soil moisture is a complex mixture of pore-scale physics and statistical properties of the soil matrix. A common problem with increasing averaging scale is that heterogeneities in soil hydraulic properties play an increasingly important role in soil moisture. As a consequence of these scaling problems, the seemingly simple problem of defining soil moisture is a theoretical challenge that has broad implications for analyzing subsurface flow and transport.

Scaling problems are directly involved in some hazard assessment and water management problems. The U.S. Geological Survey has extensively used the "Index Flood Method" by for flood frequency analysis. The rationale for the method is quite simple. A typical stream gaging station will have record lengths of 10-30 years, yet many applications require information on flood peaks with return intervals of 100 years or longer. The basic idea of the index flood method is that annual flood peak observations from a number of stream gaging stations in a homogeneous region can be combined if the observations are "scaled" to have the same statistical distribution. Under the index flood method, flood peak observations at a given station are scaled by a power law function of drainage area of the basin. Thus we can take 25-year records of annual flood peaks for 20 stations and produce a flood record with an effective length of 500 years. If this procedure works, we are approaching the sample sizes required for drawing useful inferences concerning extreme floods. Two key problems arise with this procedure. Once again, heterogeneity is not just a nuisance but also a fundamental problem. Land surface properties are not organized in such a manner that flood peaks in different basins can be characterized by distinct zones of homogeneous hydrologic response. Land surface properties that control flood response vary continuously in space with topography, land cover, soil hydraulic properties, and climate. Analyses of scaling properties of flood peaks need to deal explicitly with these heterogeneities.

A second problem is that even for relatively homogeneous regions, the index flood assumption does not hold. Scaling flood peaks by a power law function of drainage area does not result in flood records with identical distributions. Flood peak records in many locations are characterized by scales of maximum variability, typically in the range of 10-100 square miles. These scaling properties of flood peaks may result from scaling properties of rainfall, scale-dependent structure of floodplains, or drainage network properties of river networks. Unraveling these issues will provide interesting insights into hydrologic processes and enhance our capability for utilizing flood peak observations from a range of basin scales. The index flood method is typical of numerous water resource management and assessment methodologies in which scaling problems are central to development of effective tools for using data to solve water resource problems.

Scaling problems are especially difficult at interfaces in the hydrologic cycle, for at least three primary reasons: (1) the characteristic length and time scales of processes change abruptly, (2) the scales of heterogeneity of properties change; and (3) the typical support scales of measurements change (consider rain gages, wells, stream gages and moisture probes). Precipitation, for example, is the basic forcing for many land surface processes. From the perspective of infiltration and flow modeling in the unsaturated zone, precipitation provides a time and space varying boundary condition for a model of unsaturated flow, like the Richards Equation. Soil moisture, which varies in time and space, is the dependent variable that must be determined. As noted above, simply defining soil moisture is fraught with many problems of scale. To model infiltration and unsaturated zone flow, we must combine this representation of soil moisture with measurements of precipitation. Weather radar provides an important new technology for spatially continuous monitoring of precipitation, but characteristic measurement scales are associated with these observations. The minimum time and space scales for radar rainfall observations are approximately 5 minutes and 1 km^2. There is thus a scale mismatch between our best observations of the precipitation forcing and the fundamental physical representation of soil moisture. Likewise, measurements of soil moisture are typically made either in-situ at point scales (a few cm) or by remote sensing at very large scales (tens of kilometers). These problems of scale mismatch between processes, models, and data sources are characteristic stumbling blocks to solving water resource problems.

Finally, little is known about the nano-scale properties of water in the subsurface pore space . Yet this is the scale at which many biogeochemical reactions take place. Hence, understanding the potentially unique properties of water at the pore scale, and then scaling these properties from the cm- to higher scales is important for developing realistic models of hydrobiogeochemical processes.

3. LINKAGES BETWEEN ECOSYSTEMS AND THE HYDROLOGIC CYCLE

Across the landscape a mosaic of flora, fauna, and microorganisms dynamically interact with the hydrological cycle over a wide range of spatial and temporal scales, where the ratio of water stored in the biosphere to that in circulation is over 17:1. Plants mediate water transport and change water chemistry as part of an array of ecological processes operating at rates that are often the same as those for abiotic processes, although they may operate at distinctly different rates depending on the spatial scale. Ecohydrology can be viewed through physical conditions such as water stress effects on vegetation, as well as chemical conditions. The role of ecohydrology in hydrologic science research is expanding with evolving measurement technologies (from micro-probes to satellite sensors) for examining the spatial and temporal relationships that control flux, storage, and transformation of water and its constituents across spatial scales from microhabitat to channel unit to valley reach to watershed and beyond. Research on ecohydrology would be of high priority to the water resources community simply because it addresses processes of fundamental concern for understanding the healthy functioning of ecosystems. However, with ubiquitous environmental change, it is critical to not only clarify the natural rates of interactions between water and the biosphere, but to ascertain the potential limits to perturbation before the natural links between the water and biotic systems begin to break down.

In terrestrial systems, examining ecohydrology at the scale of an individual plant shows some of the problems encountered in studying interactions across boundaries. The successful growth and reproduction of an individual plant depends on a combination of genetic properties and environmental factors including water availability. Spatial patterns in fine-scale water availability for a plant are controlled by local water source (e.g., precipitation, overbank flooding, groundwater discharge), substrate type (e.g., poorly drained versus well-drained), and geomorphology (e.g., hillslope noses versus hollows). Water balance studies of individual plants have been carried out for many agricultural plant species. From these studies it is known that 99% of the water taken up by a crop may be transferred by transpiration to the atmosphere on the same day. This transfer process is inextricably linked to CO_2 assimilation and biomass production, with unknown consequences under the present atmospheric regime of increasing CO_2 concentrations. Although detailed study of this sort has been carried out for many individual plant species, the properties of an individual plant do not necessarily reflect the properties of the complex mosaic of plants typically present within plant communities outside of agricultural settings. Therefore, theoretical challenges present in ecohydrologic studies relate to both scaling of properties of hydrologic processes and to heterogeneity of the biosphere.

In the aquatic environment, patch-scale ecohydrology is of critical importance to resource management, and it addresses a different suite of processes and questions than in the terrestrial environment. Rather than focusing on the water balance to ascertain water availability and its role in plant growth and species succession, the key aquatic questions revolve around hydrodynamics, chemical cycling, and sediment transport. Often research results related to hydrodynamics are expressed by quantifying the connectivity of water bodies and reservoirs with measurements of the volumes of each water body and the flux rates among them. Occasionally the associated water constituents are also measured. For example, field research has been done to quantify how the natural flow regime controls survival, growth, and reproduction of fish species and macroinvertebrates. However, often these studies describe only a few hydrological measures such as water depth and do not yet fully incorporate information such as oxygen availability from hyporheic flow, flow turbulence structure, or sediment concentration. Research specifically designed to measure simultaneously the rates of abiotic (e.g., hydrologic processes) and biotic processes (e.g., biomass production) across the key spatial scales for both natural and perturbed ecosystems will lead to a more complete theoretical understanding of the linkages in ecohydrology.

Hydrologic controls on water quality parameters are of great importance to ecosystems. For example, in many (particularly first-order) streams, the dissolved organic carbon concentration has been shown to increase with increasing discharge, at least up to a point. Dissolved organic carbon plays an important role in attenuation of potentially damaging UV radiation. If climate change results in increased occurrence and duration of summer droughts (predicted by many models for the midwestern U.S.), then the decreased dissolved organic carbon concentrations in lakes, streams, and wetlands could result in increased UV light penetration and damage to aquatic ecosystems. Development of predictive models requires coupling climate change models with hydrologic models, with laboratory and field-scale hydrogeochemical and ecological studies.

Addressing ecohydrological linkages at a regional scale has required the use of field measurements and remote sensing data linked in numerical models. For all of these modeling approaches, the greatest limitation is the availability of spatially distributed data for model parameterization, initialization, and validation. In particular, there remains a mismatch in the input data available to truly characterize differences in scale and the degree of heterogeneity across the range of conditions that must be considered in order to produce informative results for interactions between the biotic sphere and the hydrologic cycle.

4. HYDROLOGIC PREDICTION

Hydrologic prediction problems include the following: (1) What will be the inflow to hydropower reservoirs in the Pacific Northwest during the next six months? (2) Will a plume of contaminated groundwater reach a municipal water supply well within the next 10 years? (3) Will Rock Creek flood portions of Washington D.C. within the next 24 hours? (4) What is the frequency of exceedance of a flow of 1000 m^3/s for an ungaged, snowmelt fed stream, with a drainage area of 1000 km^2 in the Rockies? (5) How will the water balance of Salt Lake County change as farmland is converted into suburbs? (6) How do summer patterns of large-scale atmospheric moisture transport change in response to large-scale groundwater-based irrigation in the central Plains?

These examples illustrate that hydrologic prediction encompasses a number of similar, and yet different conceptual exercises that may require a variety of data and methods. First, there is the operational forecasting problem, where we seek to solve an initial and boundary value problem to integrate system equations forward to the desired period in the future (e.g., 6 months, 10 years, 24 hours) and say something about conditions that may exist then. It is commonly understood that uncertainties in model parameters and boundary and initial conditions limit the predictability of such exercises, and physical-statistical modeling constructs must be employed to evaluate and communicate the propagation of these uncertainties through the chain of subsystem models used.

Although additional data and "better" subsystem models can reduce such uncertainties, predictability is fundamentally limited by the understanding of the system encoded in our models. For instance, until the relatively recent recognition of the El Niño Southern Oscillation phenomenon and the potential consequent predictability of the streamflow and intermediate ocean-atmosphere processes, an entire line of inquiry into the forecasting problem was absent, and hydrologic models were driven by scenarios of rainfall that were either non-informative for the long run, or limited to a few days into the future.

Hydrologic systems are not "closed," and the variables we have historically treated as exogenous forcing to subsystems often account for substantial variation of the state variables (e.g., flow, level) in which we are interested. As larger space and time scales are considered for forecasting, it is imperative that an integrated view of the hydrologic system across different media (air, land, water, ice) and scales (local to global) be developed. This leads to a very complex, and multidimensional system, that may yet exhibit remarkable organization. Diagnoses of these interactions across the interfaces discussed earlier, and across space and time scales to establish how slowly evolving components of the system interact with those that change rapidly, and hence affect the predictability of each, are crucial for progress on predictability and forecasting. Lagrangian models (i.e., follow the trajectory of water through the system) and exploratory data analyses guided by conceptual hypotheses are promising avenues in this direction. Techniques of "data assimilation" can provide operational corrections to model based forecasts, help diagnose aspects of models that need improvement, and make a useful supplement to an integrative, exploratory, data driven research strategy for improving forecast skills.

The second class of prediction problems of interest pertains to conditional statements that allow us to say something about the statistics of the hydrologic process given a context. Examples 3 through 6 fall in this category. Here, instead of integrating a system of equations to some specific forward time, or estimating specific values of the state variables at some spatial points at a given time, we recognize that as the hydrologic system being studied evolves, physical constraints may decree a certain structure in space and time such that in the long run certain states are preferred. Thus, we may wish to estimate the net water balance for the Great Salt Lake under landscape change contingent on "average," "wet," or "dry" climate; or the frequency, duration, and recurrence attributes of high and low stands of a closed basin lake, and the associated statistics of salinity and vegetation; or given different soil moisture and vegetation states in the central Plains, project whether the statistics of the strength and position of the summer low level jet that brings much of the moisture to the region is shifted, thus enhancing or subduing desertification in different sub-regions. There is evidence that nonlinear interactions between slope and basin scale surface and ground water systems act as switches that can lead to amplification of weakly organized seasonal and longer climate oscillatory modes to create dramatic regimes of persistent hydrologic and biotic response. The issues discussed in the context of the forecasting problem are also relevant here. In essence, gains in predictability are most likely to come from integrated analyses across the interfaces that rely increasingly on the generation and testing of hypotheses aided by the identification of patterns and structure across multivariate data fields. The accompanying integration and refinement of disciplinary, subsystem models to assimilate the diverse, multi-scale data enabled by CUAHSI's infrastructure efforts will provide further gains, but only if there is a concerted effort to understand and characterize the long term dynamics of the system.

The discussion of scaling in the earlier section, and the long standing interest in the Hurst phenomena or long memory in hydrologic systems, recognize that hydrologic data reveal organization across scales, and that the larger scales account for increasing variance in the system in a manner that is proportional to scale. We are now starting to recognize that such structures do evolve in space-time dynamical systems, as a consequence of nonlinear interactions. However, much needs to be learned about how one can build system models that leapfrog the traditional Newtonian framework and the need for parameterization at incommensurate scales, while encompassing biotic, terrestrial, atmospheric, and oceanic processes, and are yet rooted in sound science. Thus, complementary bottom up (refine data and models for describing subsystem and interface dynamics) and top down (exploratory, system level model building and data analyses) are needed to improve predictability. In this regard, while climate and other sciences have much to contribute to hydrology, hydrology has perhaps more to contribute to those sciences through a comprehensive hydrologic prediction initiative, since it provides a direct focus to the key energy exchanges and fluxes in those disciplines,

Advances in hydrologic science should lead to major advances in the "predictive" understanding of hydrologic systems. This objective implies an integrated examination of hydrologic processes in which modeling and observation play more than just a supporting role. Development of hydrologic information systems to enhance hydrologic prediction is an important element of improving our capability to adapt to changes and uncertainty in freshwater resources.

5. WATER RESOURCES MANAGEMENT

In a changing and increasingly uncertain environment, effective use and management of water resources must be scientifically based. But greater scientific understanding does not automatically translate into more effective use and management of water resources. The latter requires the development of methods that exploit new scientific understanding as well as attention to the processes controlling the adoption of new methods.

New predictive tools offer great promise for improving the use and management of water. Intermediate-term probabilistic forecasts based on an improved understanding of climate predictability could be used to partition water storage between flood control and water supply and condition seasonal water use. New decision models are needed to achieve this potential. New decision models are also needed to capture the benefit of improved understanding of and ability to model nutrient transport in watersheds.

Climate uncertainty presents an enormous challenge to water resource managers. Traditional design and management of water resource systems has been predicated on statistical methods that assume stationarity. For example, flood-risk assessment and the design of flood conveyance, storage, and protection are based on the assumption that the meteorological component of flood risk is constant from year to year. However, we now know that this assumption is questionable because of low-frequency climate variations due to natural and anthropogenic causes. A new paradigm that accounts for these variations is critically needed.

Research on the processes controlling the adoption of new methods is also needed. Many legal, political, and social factors constrain the application of science to water resource problems. For example, the use and management of water does not usually recognize the interrelationships between various sources and stores of water. Surface and ground water are usually managed separately, despite their strong interconnections. Urban and rural water management are rarely coordinated. In urban areas, water supply, stormwater, and wastewater are usually managed by separate agencies that rarely coordinate their decisions. It is clear that significant efficiencies can be achieved by coordinating the use and management of water across natural and human boundaries. Research is needed to develop and evaluate methods to achieve such coordination within the existing socio-political framework.

Another factor impeding the application of science in water use and management is the extremely slow rate at which new science-based methods are employed, either to assist in problem analysis or to solve problems. Consider the following examples:

- Continuous hydrologic simulation, although supported by over 30 years of research, is often not used in applications where it would clearly improve decision-making.
- Estimation of flood risk is almost exclusively based on methods developed before 1980, in spite of many significant improvements in statistical methods.
- Hydrologic predictions are not commonly used to support water use and management.
- Infiltration practices, although long recognized for their potential benefits for urban stormwater management, are only haphazardly applied.

Many explanations for not adopting these new methods exist, including insufficient documentation, lack of successful demonstrations of benefits, lack of proper training, regulatory inertia, and lack of incentives for innovation. Research is needed to better understand the process inhibiting the adoption of new methods.

When considering any major research initiative on understanding and adapting to hydrologic change, it is critical to recognize the extent to which the components of the hydrologic cycle, and the various aspects considered in our other research objectives, are influenced by engineering infrastructure and water resource management decisions:

- There are very few rivers of any size in the continental U.S. that do not have dams or some form of control structure modulating the annual cycle of runoff and transport of solids.

- Large-scale interbasin transfers of water have altered the hydrologic budget. This is particularly true in regions of relative water scarcity; the Colorado River system, for example, has been described as "A River No More" and has also been depicted as an elaborate plumbing network. There is an often-quoted adage to the effect that in California, water flows uphill toward money. Interbasin transfers are common even in areas of relative abundance, as seen in South Florida and the Everglades, or the water-supply systems of metropolitan areas like New York City.

- Major aquifers, particularly in the High Plains and the western U.S., suffer from overdraft and declining water tables, subsidence, saltwater intrusion, and contamination by agricultural and industrial chemicals. In some areas there are efforts to mitigate quality problems through extraction, treatment, and reinjection of groundwater; enhanced storage in aquifers through the use of injection wells is another aspect of engineering infrastructure.

- In urban areas it is often difficult even to define watershed boundaries, much less the urban water budget. "Natural" subsurface flow systems interact in unknown ways with underground utilities, building foundations, tunnels, and water and wastewater pipe networks. Imported water from reservoir watersheds is sent throughout the distribution system within the urban core and, sometimes, nearby suburban jurisdictions, with unknown amounts and locations of leakage into groundwater, storm drains, and local streams. Wastewater systems are designed to carry return flow to wastewater treatment plants whose discharge point may be located in yet another watershed. Yet these often leak, also in unknown amounts and locations, affecting local water quality and water budgets, augmenting urban flow and contaminant loads in low-flow periods, and affecting water quality through combined sewer overflow or spillage of clogged or overloaded sanitary sewer networks in high-flow periods.

- In urban areas much of the natural drainage network has been replaced with a much more efficient network of storm drains. There is some research indicating that these are as important as, or even more important than, the amount of impervious cover as an influence on stormflow and flood potential. In the past couple of decades many jurisdictions have interposed a series of valves in some portions of the urban/suburban drainage network through construction of stormwater detention basins with the dual purpose of reducing peak flows and storing non-point source pollutants. The integrated operation of these systems is poorly understood since the pieces are designed and placed individually rather than as an integrated network. Clearly these are managed systems, but they have been managed on an ad hoc basis with little or no guidance from management science.

- Public agencies and private groups presently are carrying out a second generation of river projects in the United States attempting to improve riverine conditions by returning them to a more natural condition. While the 20th century was replete with river projects that sought to tame and convert rivers for human use, widespread efforts are underway to make the 21st century an era of returning rivers back to natural functioning. The need for such efforts stems from the well-documented loss of in-channel and streamside habitat, extensive river regulation, increasing flood risks and flood damages, changing societal attitudes, and the poor water quality of American rivers with ~50% non-fishable and non-swimmable. However, limited theory and data are available to guide the current efforts, which results in risky experiments yielding little or no basis for scientific advancement. In many cases, these experiments result in trade-offs in which hypothetical gains offset the destruction of well-functioning natural areas. Furthermore, larger scale integrated watershed management is rarely considered in localized project designs. If the science of river restoration and rehabilitation is not pursued aggressively, it is highly likely that the era of well-intentioned projects will merely serve as an efficient mechanism for further destruction of the environment.

As we ask more of our water systems, we must manage them more carefully. This is especially evident at regional scales where so many objectives and interests conflict, but where a wide variety of demand and supply quantity and quality management options exist. Some particular examples include: (1) conjunctive use of surface and ground waters, (2) managed water reuse, (3) water exchanges and markets, (4) incentives for local water management with regional benefits, (5) land and substance management and water quality, (6) human behavior and perception in water conservation and water quality, and (7) integration of options for safe and effective system performance. Science and management should be brought together. Many promising management ideas make new demands on hydrologic science. Financial and institutional models for understanding and improving regional water management in pluralistic settings are needed.

The demand to restore natural habitat in streams, rivers, floodplains, and wetlands has profound implications for water management and the direction of hydrologic science. Technological advances based on hydrologic science are no longer directed solely to human needs, but also must serve a diverse variety of species over a wide range of hydrologic conditions, typically within the context of a human-managed ecosystem. The hydrologic basis of the human and natural world must be sufficiently understood so both can be better served simultaneously. Then, hydrologic science must also be better incorporated into management, planning, and policy decisions and institutions. In the contemporary political environment, such knowledge must be developed and function within a pluralistic setting of many stakeholders, interests, and agencies.

Human exposure to carcinogens, toxics, and pathogens through drinking, bathing, or other pathways remain fundamental motivations for water management and hydrologic science. The chemistry and biology of water and risk analysis within the hydrologic cycle remain important topics within the context of local and regional water management. The management of health risks over a variety of groups of individuals within a regional system poses organizational and scientific challenges.

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