Hydrology of a Dynamic Earth

A decadal research plan for hydrologic science

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Consortium of Universities for the Advancement of Hydrologic Science, Inc.

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Hydrology of a Dynamic Earth

A Decadal Research Plan for Hydrologic Science

Overview: Scientific Understanding of a Vital Resource

The Earth is changing around us. At geological time scales the Earth has always been dynamic, but lately change has become more rapid. Humanity has impacted the earth in many profound and potentially irreversible ways. The earth surface has been colonized, converted to agriculture or urban landscapes. The atmospheric composition has been changed. The scale and magnitude of these changes has led the hydrologic science community to adopt the following goal for the coming decade:

> To predict water availability and quality in order to support sustainable development under the threat of significant human-induced change enabled by advances in distributed sensing and cyberinfrastructure.

Climate change. Global circulation models predict significant temperature changes over the next century, and, with less certainty, predict changes in precipitation. Knowing that the temperature or even annual precipitation amounts are changing is only one step towards estimating what the true societal impacts are. Can crops still be grown in the same places? Is water distribution infrastructure still adequate to meet demand reliably? If more rain falls in extreme events, how will the partitioning of precipitation at the land surface among infiltration, runoff, and transpiration change thus changing the water available for human use? Will temperature changes shift plant communities and change transpiration demand on water? Predicting these effects is far more difficult for the terrestrial environment than for the atmosphere because, unlike the continuous fluid of the atmosphere, the terrestrial environment is highly heterogeneous, adaptive biological processes control much of the terrestrial system, and the observations of the subsurface are very limited.

Human development. At the same time as climate change may cause shifts in precipitation, human development of water resources is reaching unprecedented levels. Population density in coastal areas is stressing water supplies. Agricultural irrigation is overdrafting groundwater. Citizens are demanding water for maintenance and restoration of aquatic ecosystems. Traditional solutions, whether structural controls for flood protection or end-of-pipe treatment of waste are inadequate to address the problems faced by society. In all these cases, the knowledge base is lacking to make scientifically informed judgments that allow us to make rational investments in hazard protection or to make trade-offs among competing economic, social, and ecological demands on water.

Consider the following:

- *We do not know how much water is available.* Although there are thousands of rain and river gages, we routinely monitor only these two components in the hydrologic cycle. We have no dynamic estimates of the stores of water available within a river basin. In some areas where groundwater is an important water source, withdrawals are measured. However, estimates of groundwater recharge are not widely available and imprecise where we do have them. Hence we don't know what the sustainable rate of water use for a river basin is.
- *Water in the river today may have fallen as rain decades to centuries ago.* Only within the last 20 years have techniques been developed to estimate the age of "young" ground water. The results have been surprising. Even in quite small river basins, a rain drop takes considerable time to travel to the river. Hence contaminants that the water carries, such as nutrients, may take decades before they appear in a river and, similarly, clean-up efforts may take decades to show any effect. Our knowledge of travel time for sediment, the transport vector for hydrophobic contaminants, is even more limited than for water.
- *We cannot reliably predict the effect of a change in precipitation on water availability or water quality.* The response of a river basin to a change in annual average precipitation depends on a number of factors—its distribution and form, for example—yet, even if those are specified, we can't say that a given increase in precipitation will result in a proportional increase in runoff. Predicting the indirect effects of precipitation change is still more uncertain: we can't predict reliably if nutrients or sediment transport would increase or decrease in response to a 10% increase in annual precipitation because of the interactions among physicochemical and biological processes.

In light of the unprecedented changes the Earth is experiencing, the need for reliable predictions of the response to the surface Earth System—hydrologic, biogeochemical, and soil-forming processes—over the next century to predicted changes in climate and in human population is a pressing societal need.

To meet this challenge, a more comprehensive and a more systematic understanding of *continental water dynamics*—that part of the global water cycle acting over and on the continental land masses and involving the dynamic interaction of water with landscape, ecosystems, and civilization—is necessary. At the most general level, continental water dynamics requires prediction of fluxes and stores of water throughout the continent, of the pathways water takes through and among these stores and of the velocity along these pathways. These four fundamental properties—stores, fluxes, flowpaths and residence time of water—link continental water dynamics with ecology, biogeochemistry, geomorphology, and climatology. Understanding these properties will permit prediction of direct and indirect effects of human activities and climate change on our water resources and on our planet.

A deeper understanding of continental water dynamics will allow our nation to better prepare for the challenges posed by changes in the terrestrial water cycle that result from climate variations and human activities. This report proposes a community research strategy for the coming decade around the following three issues:

1. **Linking the hydrosphere and the biosphere**. Recent research in ecohydrology has shown the interactions among biological, soil, and hydrologic processes are strong and adaptive. Traditional views of a one-way hydrologic forcing of the biological system do not capture these interactions and adaptations. Soil moisture, a poorly measured store of water, has emerged as the “gatekeeper” linking atmospheric, biological, and hydrologic processes
2. **Upscaling hydrologic, biogeochemical, and geomorphic processes**. Our current understanding of these linked processes comes from laboratory simulations under controlled conditions and field studies at relatively small scale. We need to determine whether these processes combine in a predictable way to control macroscale processes or if there are emergent properties at larger scale that have higher predictive powers. The generality of results found at any one site must also be assessed to establish this hierarchy.
3. **Predicting the effects of climate change and human development on water resources.** With the understanding developed under the first two issues, we can more reliably make these predictions. A fundamental goal of hydrologic science is to be able to predict the response of water and the entire shallow earth system to human and climate perturbations to a level of confidence approaching those now possible for atmospheric and ocean systems, despite the heterogeneous nature of the continental environment.

These three challenges share the same science requirement: understanding the controls on stores, fluxes, flowpaths, and residence time of water so that estimates of these properties can be made at sufficiently large scales to be meaningful for resource management.

To comprehensively address these challenges requires coordinated investigation and large scale infrastructure that extends across the scale of continents. The Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) has been formed by the academic hydrologic science community in the U.S. to develop plans for and to promote the establishment of the large-scale infrastructure needed to address these questions in a coordinated fashion. Such infrastructure could not be established by the CUAHSI member universities or individual investigators acting alone. Such infrastructure is a necessary complement to existing single-investigator research.

For the hydrologic science community to realize these opportunities requires four key ingredients:

1. *New observations*. Gaining new understanding of continental water dynamics requires integrated observations of the hydrologic cycle, particularly at the interfaces in that cycle, such as the land surface and atmosphere or groundwater and surface water.

Existing data are spatially incoherent—rainfall is measured at one place, groundwater at another and soil moisture at a third, as well as too sparse to test hypotheses. Furthermore, multiple lines of evidence, such as the use of chemical tracers, are needed to add power to such tests. The development of *coherent* multidisciplinary data sets is a central goal for the hydrologic science community.

2. *Multidisciplinary synthesis*. Novel insights can be gained through the integration of new observations, theories, alternate methods of analysis and broader interdisciplinary perspectives. CUAHSI has described a synthesis facility for hydrologic science in a white paper (CUAHSI Technical Report #5) and two synthesis projects are underway to serve as demonstration projects.
3. *A modern information system* for data access and modeling. The CUAHSI Hydrologic Information Systems project, now in its third year, has been developing the prototype applications to federate multiple data sources including data from various federal and state agencies as well as data from academic scientists. This project is also laying the groundwork for modern modeling frameworks that improve the efficiency of modeling and enhance model comparison by allowing scientists to contribute to a common library of interoperable modules. Computer simulation models, as precise quantitative statements of our hypotheses, will play a central role in this community research strategy.
4. *Advanced instrumentation*. The range of instruments used by hydrologic scientists is vast and rapidly growing. It ranges from geophysical exploration of the subsurface, to atmospheric scintillation, to laser spectroscopy to measure stable isotopes of water, and, while no one scientist can be an expert in all these areas, addressing the community challenges requires data from all phases of the hydrologic cycle. A pilot project for a Hydrologic Measurement Facility has been underway since 2005 exploring how to get sophisticated instruments, along with the necessary training on how to use these instruments, into scientists' hands.

Although increased understanding of hydrology of a dynamic earth requires new observations, determining where to collect new observations, when to collect them, and how frequently to collect them is complicated by the spatial heterogeneity and dynamism of the continental environment. Three stages are proposed for evaluation: (1) *benchmarking current understanding* through the use of simulation models on “digital observatories” constructed from existing data records (including remotely sensed data and paleodata), while *prototyping new observational systems* to test environmental robustness, (2) *testing generality of understanding* through cross-site comparisons using measurement campaigns of limited duration which build on information from fixed-place observations of longer duration, and (3)*understanding long-term response* of hydrologic systems to climate and human impacts through the establishment of an expanded network of place-based observatories. These observatories will build on existing research and monitoring networks to develop the inferential capacity to make reliable predictions of water stores, fluxes, flowpaths, and residence-time distributions. The third stage is the most expensive and one whose merits must be carefully evaluated. Emerging observatory activities that include some hydrologic component, such as the currently proposed Critical Zone Observatories, the National Ecological Observing Network (NEON), and the WATer and Environmental Research Systems network (WATERS) test-bedding activities , are essential to inform the design of fixed-place hydrologic, their relation to shorter-duration measurement campaigns, and to the other existing or emerging long-term observational programs.

Each of these areas— observations, synthesis, informatics, and instrumentation—provide outstanding opportunities for education and outreach at all levels from grade school to citizen engagement. Water is a substance we all need and something with which we are all familiar. Yet much of the hydrologic cycle is hidden. Public understanding of groundwater (and aquifers), connections between different phases of the hydrologic cycle, and the role of continental water dynamics in the global water and energy cycles is limited. The decadal research strategy includes various outreach efforts, generally building on existing outlets such as science museums, but also supporting the academic community to improve undergraduate and graduate research experiences.

The maturation of hydrology as an inter-disciplinary science and the impact of unprecedented perturbations on the water cycle, which has great importance to human existence, make this a crucial period. The proposed community science plan will enable reconstruction of past histories, promote important new measurements, deploy modern sensor technology, employ cyberinfrastructure to synthesize data and models, and integrate disciplines. It will combine knowledge from the past with observations of the present to make possible predictions of the future of continental water dynamics.

1. Continental Water Dynamics

1.1 Definition

Continental freshwater is part of the planet-wide water cycle also involving the oceans, the atmosphere, the biosphere, and the cryosphere. But continental freshwater plays a special role; it is the component of the water cycle that links most other terrestrial environmental sciences, sustains life on land, and directly affects the prosperity, safety and economic viability of a nation.

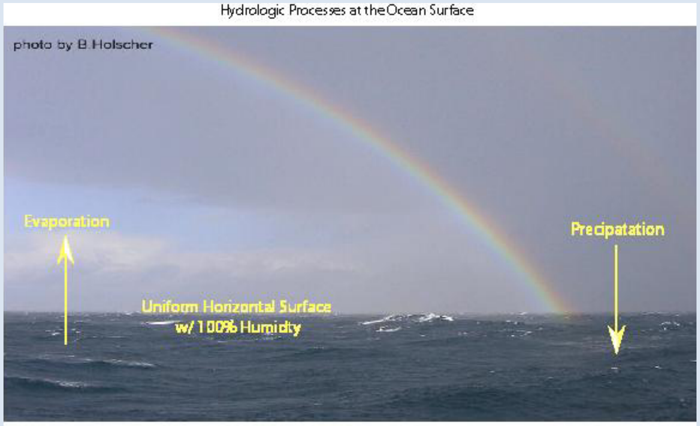
Continental water dynamics describes the dynamic interaction of water with the atmosphere, landscape, ecosystems, and humans, including human-built water infrastructure.

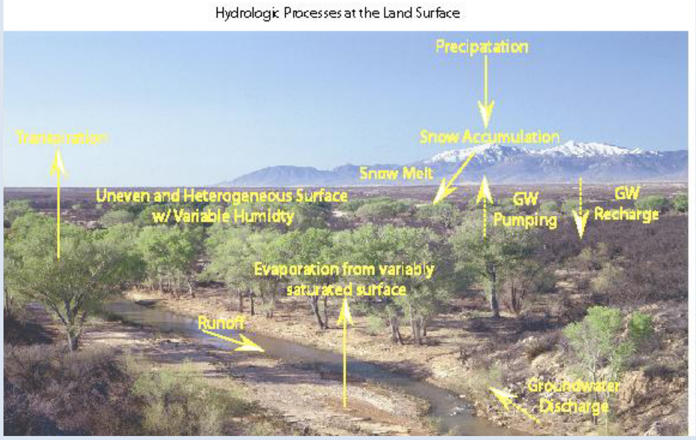
Research of continental water dynamics crosses all spatial scales, examining water-related states and fluxes on hillslopes and headwater streams, in river basins and regional aquifers, and across the nation. It examines temporal variation and change, spatial patterns and heterogeneity, and the emergence of new behavior at larger scales. Research also seeks to quantify the physical, chemical, and biological processes that influence water resource through the collective use of theory, manipulative experiments, observations and modeling.

Compared to oceanic water dynamics (see sidebar), continental water dynamics is more strongly controlled by biological and geologic processes and exhibits many nonlinear feedbacks. This difference presents a series of challenges in developing the theories needed for prediction of continental water dynamics. First, spatial heterogeneity in the land surface complicates measurement strategies; unlike the ocean and atmosphere, the earth is not a continuous fluid. Second, temporal dynamics of hydrologic response to precipitation are non-linear and exhibit threshold behaviors requiring that measurements be made at sufficiently high frequency and accuracy to capture this response. Third, accessing the subterranean portions of the hydrologic system is difficult; even deploying instruments can alter the properties that we seek to measure. Finally, and most importantly, the continental environment itself is changing from natural processes and human activities; water both responds to and is an agent of those changes.

Each of these challenges present opportunities for advancing scientific knowledge. To realize those opportunities, CUAHSI recommends an integrated strategy of observations, synthesis, informatics, and instrumentation. This strategy will enable reconstruction of past histories, will promote important new measurements, will deploy modern sensor technology, will employ cyberinfrastructure to synthesize data and models, and to integrate disciplines. It will combine knowledge from the past with observations of the present to make possible predictions of the future of Continental Water Dynamics.

Surficial Processes on the Ocean and the Continents. The complexities of the Continental Water Dynamics are illustrated by comparing the hydrologic processes operate over the ocean surface with those of the terrestrial environment. Over any one patch of ocean there are essentially two hydrologic processes of importance: precipitation and evaporation (top figure). In this environment hydrology is an entirely *physical* system and estimating rates for processes are relatively straight forward because the ocean has a free-water surface at 100% relative humidity.





In contrast, these same two processes are greatly complicated in the terrestrial environment (bottom figure) due to the topographic, soil, vegetative, and land use heterogeneity of the land surface. For example topographic gradients control precipitation amounts and variably saturated surfaces strongly control the rates of evaporation. Partitioning of water at the land surface is controlled by these and other physical processes, including infiltration, groundwater recharge and discharge and surface runoff, and by *biological* processes, notably plant transpiration. Many of these processes, because they occur below the land surface are difficult to directly measure. Finally human water use, through groundwater pumping, surface water diversions, and agricultural and urban development and demands, have greatly altered the hydrology across the continent and around the world. These complexities of the terrestrial environment, especially these heterogeneities, represent the challenge of terrestrial hydrology. (*Contributed by James Hogan, University of Arizona)*

1.2 Advancing Continental Water Dynamics

To understand the opportunities for advancing our understanding of Continental Water Dynamics, the challenges presented by the continental environment must first be presented more completely. There are three key areas. The first two include the temporal and spatial heterogeneity of the continental environment. The third is a challenge of modeling and prediction in an observational science where our ability to perform controlled experiments is quite limited.

1.2.1 Variability, Change and Adaptation

Continental Water Dynamics describes the dynamic temporal variation of processes and responses, from minutes to daily, seasonal, and inter-annual swings of water-related fluxes and stores, to rare and episodic events. But it also must grapple with long term change of average conditions, of the magnitude of swings, and of the propensity for rare events. Continental Water Dynamics focuses on detecting, attributing, understanding and predicting variability and change. Progress in this area will allow science and society to discriminate change from variability, and to adapt to and manage both of these under uncertainty.

Rare and Episodic Events. Many of the most important dynamical processes occur during episodic or extreme events. These include rare pulses of water, sediment, contaminants, and nutrients that often are unobserved during average conditions. Limnologists currently cannot predict the stream transport of carbon and nitrogen associated with major hydrologic events, when biogeochemical action is most intense. Geomorphologists realize that most landscape evolution occurs during some of these same events, but the majority of their understanding is based only on studies in pristine headwater catchments. Groundwater hydrologists in the semi-arid Southwest suspect that it is a rare series of precipitation events that sufficiently wet the soil to escape capture by thirsty plants and recharge aquifers, but have not directly observed this process. Water resource specialists know drought is the major limit to human development in water-stressed regions, but cannot predict drought or its consequences without considerable uncertainty.

Change. The broader scientific community has produced convincing evidence that, because of the effects of natural processes and human civilization, the Earth is experiencing environmental changes of a historically unprecedented magnitude. In the next hundred years, most areas will likely undergo major changes in temperature, and changes in regional precipitation. Long-term shifts in the water cycle, with implications for continental water dynamics, especially floods and droughts, are considered a primary aspect of these climate-related changes. While estimates of global temperature rise are consistent among researchers, especially those using climate models, predictions of precipitation responses are highly variable and uncertain. Even if average precipitation doesn't change, any shifts in temperature are expected to change the intensity, distribution, and even the type of precipitation. We've already detected less precipitation as snow and earlier snowmelt in the Pacific Northwest, with important implications for water resources management. Landscape and vegetation are also changing, due to both natural geomorphological and ecological processes, and human engineering of landscapes for living space, agriculture or other purposes. Whether abrupt or smooth, episodic or rare, these changes will impact continental water dynamics, the environment, and people, across a wide range of space and time scales.

Adaptation. Although transpiration, a biological process, constitutes a major flux of the hydrologic cycle, this process, like many other biologic processes, was always considered driven by water and energy availability. Only with the ability to directly measure transpiration fluxes through the use of sonic anemometers and large aperture scintillometers, has it become apparent that vegetation play a much more active role in the hydrologic cycle. Plants adopt strategies to improve their competitiveness in water-stressed environments such as translocating water between soil horizons and altering root distribution in response to hydrologic conditions. Therefore, any hydrologic predictions of response to different climate conditions must consider the possibility that vegetation will adapt to the new regime and alter transpiration from what is currently observed.

1.2.2. Spatial Heterogeneity, Scaling and Emergent Behavior.

Hydrologic and related processes exhibit natural spatial heterogeneity, as well as structured variability, such as that imposed by river networks and gradients in the landscape, and in soils, geology, and vegetation. Spatial patterns and heterogeneity need very dense observations to be accurately characterized. While remote sensing products may provide adequate information on land cover and land use, the state of vegetation, and even stream network morphology, they provide highly uncertain estimates of precipitation, soil moisture, vegetation transpiration, and aquifer recharge. These remote sensing estimates provide little information on geological heterogeneity in underlying aquifers and the amount of flow or nutrient load in streams. Moreover, even remote sensing products must be assisted by land-based observations for “ground-truthing” and by process understanding for extrapolation to ungauged or poorly monitored basins and also to future, yet unobserved, conditions.

Research in continental water dynamics crosses all terrestrial scales. Horizontally, it ranges from hillslopes and headwater streams (1 – 1,000 m), through river basins and regional aquifers (1 – 10,000 km), to the whole continent. Vertically, it peers downward at the microscale of a single soil pore, leaf stomata, or biogeochemically active microbial community, and upward at the entire continent. As scale increases new levels of complexity are introduced, to the soil profile, to the atmospheric boundary layer. Processes and properties can no longer be explained by simple upscaling methods from the finer to the coarser scale; instead, at each level of complexity new processes and properties emerge. Without a proper understanding of the physical basis and scales of these emerging properties, our predictive ability will remain limited both in scale and in accuracy. On the other hand, the presence of patterns and emergent behavior, if properly understood, can enhance predictability even with limited observations. This presents a unique opportunity in the hydrologic and related sciences. To take advantage of this opportunity however, a systematic observing system is needed that will collect observations of a suite of environmental interacting variables over a large range of space and time scales and subject them to rigorous analysis and comparison with physical process-based understanding and model predictions.

1.2.3 Modeling and Prediction in Continental Water Dynamics

Like all earth sciences, hydrologic science must infer mechanism primarily from observational data rather than from controlled experiments. Digital simulation models have been used extensively in hydrology, but often as tools to design water supply infrastructure or to predict the effects of management actions, such as pumping an aquifer or harvesting a forest. To advance the hydrologic science, as opposed to operational hydrology, simulation models are used to test hypotheses. In observational systems where we cannot control (or even measure) all parts of the system, the ability of the model to match observations of runoff or chemical concentrations at the watershed outlet does not mean that the hypothesis contained within the model are the only possible explanation for the observations. The relatively low information content of the calibration signals means that one can be right for the wrong reason—that is, the hypothesis may appear to be supported by the data but have low predictive power under different conditions. Ideally, multiple working hypotheses should be explored to identify environmental conditions when they yield different predictions to permit discrimination among the competing hypotheses. This has been impractical until recently given the effort required to develop complex simulation models. Getting the right answer for the right reason is not a simple undertaking (Horton, 1931; Kirchner, 2006).

Scientific understanding of hydrologic systems rests on physically based “laws” that have been developed at the microscale. Most simulation models are built on the assumption that these laws can be directly upscaled to predict water dynamics at the watershed, basin, or even global scales. An active area of research is whether this upscaling assumption is justified (e.g., Seibert, 2003). Kirchner et al. (2000) and Kirchner et al. (2001) provide an example of how new data (high frequency measurements of a conservative tracer) combined with an analysis technique developed in astronomy (spectral analysis of irregularly spaced time series) can yield new theoretical understanding of water transport (the lack of a characteristic flowpath length in a hillslope) that wouldn’t have been derived from a direct upscaling of microscale theory. Therefore, progress in continental water dynamics requires an active debate about upscaling properties. Community support of this debate includes providing both novel data sets and analytical approaches.

Another prediction challenge for hydrologic science is assessing the generality of findings. In a place-based science, how do we transcend the uniqueness of place? Given the spatial heterogeneities of the continental environment and each place’s unique geologic and human history, it is difficult to know to what extent the findings depend on idiosyncrasies of the particular field site. Testing hypotheses in multiple locations is currently very difficult and expensive because comparable data sets do not generally exist. Determining a more efficient way to conduct multi-site comparisons is a community challenge for hydrologic science.

1.3.3 Opportunities

Despite the challenges posed by the continental environment, the opportunities for collecting spatially dense and temporally frequent data afforded by new sensor and networking technologies are immense. Examples include the ability to directly measure actual evapotranspiration at the scale of hundreds of square meters through eddy covariance techniques and, at even larger scales, through large aperture scintillometers. Temperature-based sap-flow measurements enable estimation of water use by individual trees at sub-daily frequencies. Measurement of soil moisture through time-domain reflectometry has been simplified through miniaturization. Geophysical techniques have been adapted to measure properties of the near-surface that give unprecedented insight into aquifer structure and water dynamics. Some solutes can be measured at high frequency and high precision with field-deployable “labs in a can” and stable isotopes of water can be measured using laser spectroscopy in the field for one-ten-thousandth of the price of lab analysis. Wireless communications make field deployment, even in complex terrain, more feasible than ever before, and at larger scales that permit more direct application of research results to water resource management.

These technologies promise to revolutionize the study of continental water dynamics, especially when these technologies are deployed in a coordinated manner.

At the other end of the spectrum, remote sensing techniques, including LIDAR from aircraft (see Sidebar) as well as satellite-based sensors provide data at an unprecedented scale. These data provide a new view of the earth that facilitate development of new hypotheses and modeling approaches. Access and use of these data pose important challenges, including processing and interpreting massive data sets (McLaughlin, 2002). Only a small portion of the hydrologic sciences community takes advantage of such data today because of these barriers; making such data accessible and interpretable to the broader community is a goal of CUAHSI.

Ground-based sensors will be deployed in fixed-place observatories and in shorter-duration campaigns. In both cases, ground-based sensor networks will be designed to take maximum advantage of spatial data, particularly from satellites. Highly specialized instruments used for shorter-term deployments will be maintained by CUAHSI’s Hydrologic Measurement Facility.

Hydrologic Science

Hydrologic science studies the occurrence, distribution, circulation and properties of water, and its interaction with a wide range of physical, chemical and biological processes, acknowledging also the added complexity of social and behavioral sciences (NRC, 1991).

In the 15 years since 1991 NRC report, the efforts of individuals and small collaborations have significantly advanced understanding of individual components of continental freshwater in both natural and human engineered systems. For example, motivated by societal concerns with groundwater pollution, impressive strides were made toward characterizing geological heterogeneity and predicting its influence on subsurface fluxes and behavior of water, chemicals, and microbiota. The boundary between the atmosphere and the land surface became the focus of intense research efforts aiming to understand the influence of soil moisture and surface inhomogeneities on atmospheric processes, and the nature of water, energy and carbon fluxes from and to the atmosphere. The theoretical and modeling developments were aided by a spectacular suite of land and space-based observing platforms and campaigns (see Box) which resulted in innovative land-atmosphere modeling approaches such as Large Eddy Simulation (LES).

Geomorphologists have long recognized that stream channel networks, which control the space-time behavior of many water-related fluxes, form spatial patterns that look similar across a wide range of environments and scales. Over the last fifteen years there has been a revolution developing quantitative tools to simulate, measure, and explain these networks, their similarities, and their controls of fluxes of water, and more recently, sediments and nutrients.

Without solid underlying theories of the interconnectedness of the physical, chemical and biological processes, the use of observations in constraining and guiding future improvements in predictive models, and development of generalized theories that can transcend place and time, the complex water problems of today cannot be addressed. Continental Water Dynamics aims to develop the scientific basis for a holistic and comprehensive approach to solving complex water problems in service to society.

Concurrent with the development of sensor technology, information technologies have also advanced rapidly. CUAHSI's Hydrologic Information System (HIS) project has been applying web services technologies to enable federation of data from various federal agencies (including the US Geological Survey, National Climate Data Center, Environmental Protection Agency and others). Eventually, academic scientists can be included in this federation by registering their data sets with a central catalog. This approach is being tested with 10 projects currently being funded by NSF as "test beds" for the proposed WATERS Network.

From the user's point of view, CUAHSI HIS will provide a seamless environment for accessing data from multiple providers directly from within the modeling environment of their choice (Figure 1). The remote data sources act as if they are local data bases.

These web services also serve as the basis for the development of a community library of model modules and analytical techniques. Providing a community modeling framework that simplifies model development and encourages model comparison is an important goal for CUAHSI.

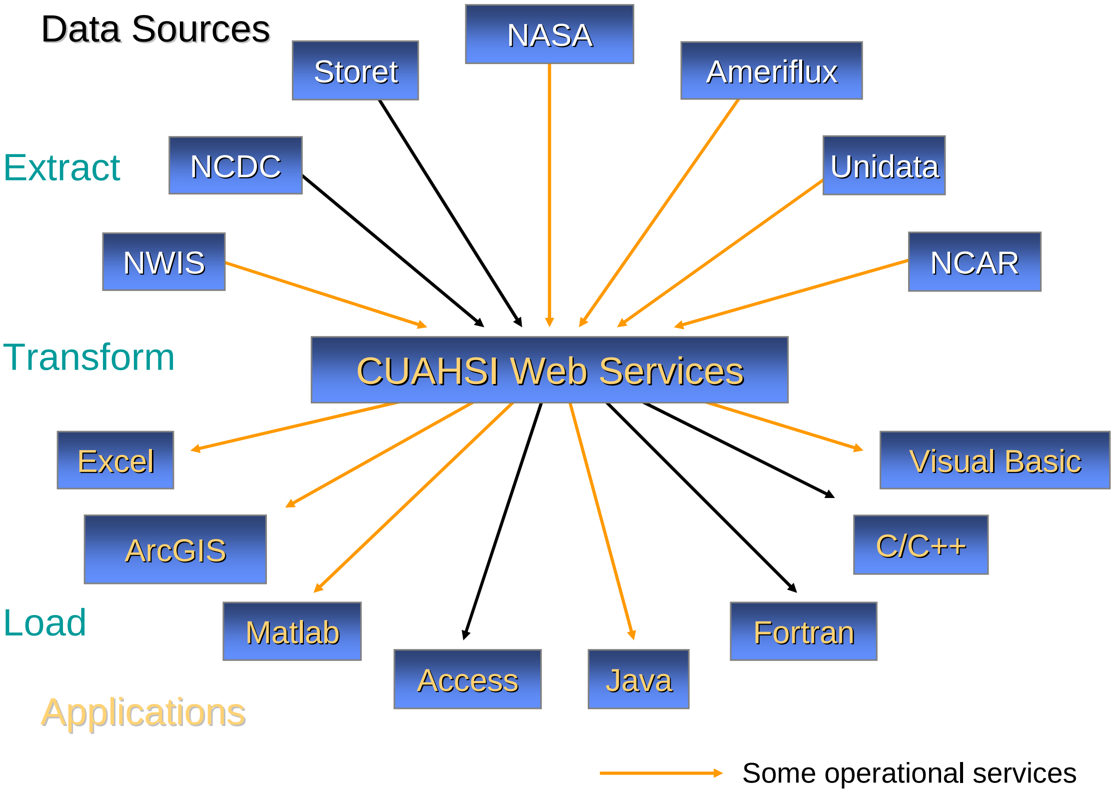


Figure 1. CUAHSI Web Services permit extraction of data from multiple providers, transformation of that data into various formats and loading data directly into various analysis environments.

New Observational Techniques: LIDAR. Geosciences is witnessing an era of rapid development of new sensor technology and observational techniques that are poised to revolutionize our understanding, and thus predictive modeling capabilities, of earth surface dynamics. High resolution topography (e.g., 1 m topography data from LIDAR) and wireless sensor technology with embedded networked sampling (e.g., concurrent and adaptive sampling over large spatial coverage and short time intervals; and particle-tracking techniques) provide an opportunity to bridge the gap between the small scales at which bio-geochemical processes occur and the larger scales at which organizing patterns are observed. Wireless technology, smart sensors with controlled activation capabilities, e.g., during extreme floods or high temperatures, small sensors that can be attached to moving gravel ("talking stones") [*McNamara and Borden*, 2004], isotopes for dating, and radar imaging, can all work synergistically to sample processes at scales ranging from a few mm and seconds to planetary length and time scales. However, despite the extreme spatial and temporal variability and the large range of scales of interacting processes, one cannot sample everywhere and all the time. Thus the challenge exists to use even rudimentary knowledge of the underlying variability, of cause-effect relationships, and of possible scaling relationships to optimize sampling network design. To that effect, detailed knowledge of topography is expected to play a significant role.

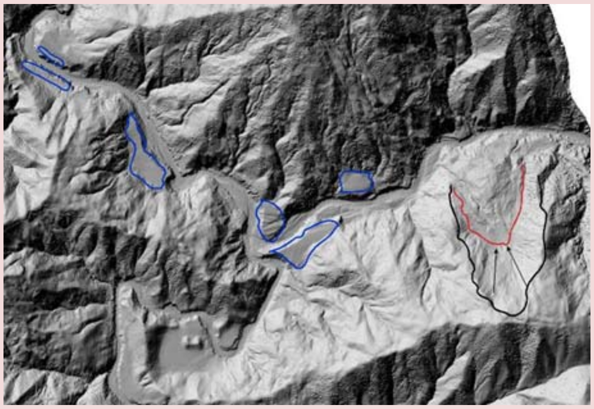


Image created from LIDAR data. Note excavation on right (orange and black outlines) caused by a landslide, and the resulting deposits downstream in the Eel river (outlined in blue). Eel River flow is from right to left. Image courtesy of William Dietrich, NCED

The newly available high resolution LIDAR topographic data [*Carter et al.*, 2001] provide the opportunity to resolve channel and floodplain morphology, stream corridor geometry (including geomorphologic disturbances at confluences), and vegetation characteristics throughout the basin. Having such high-resolution channel morphology continuously available along stream reaches and over the whole watershed offers the potential of understanding cause-effect relationships between channel attributes and biological and geochemical processes. Such relationships can guide efficient design of environmental observatories and also guide efforts to upscale local processes, e.g., algal production [*Hondzo and Wang*, 2002], and denitrification potential to stream reach averages, and ultimately to indices characterizing the state of the whole watershed. However, existing methods for defining channel heads from 90 m or 30 m DEMs do not perform well when applied to the extraction of topographic features from 1 m LIDAR data. New "geomorphologically-informed" image processing techniques are needed to take advantage of the rich information provided by these sensors, including the automatic mapping of service roads and skid trails created during logging that are large contributors of sediment to the streams. –Contributed by E. Foufoula and W. Dietrich

Synthesis of existing data sets has been identified as a third opportunity to advance continental water dynamics. The ecology community has pioneered the use of a physical facility, that National Center for Ecological Analysis and Synthesis (NCEAS), as a venue for self-forming working groups to come together with post-doctoral research associates and sabbatical visitors. The result has been a series of highly influential publications. Given the multidisciplinary nature of continental water dynamics, the large amount of existing data, and the development of services from HIS, the hydrologic science community has called for the creation of a synthesis facility (CUAHSI Technical Report #5, 2003).

Access to these three community services—information systems, instrumentation, and synthesis—are the foundation for advancing our understanding of continental water dynamics.

2. Community Science Goals

CUAHSI has chosen three community science goals around which to organize our activities:

1. linking the hydrosphere and biosphere,
2. upscaling hydrologic, biogeochemical, and geomorphic processes, and
3. predicting the effects of human development and climate change on water resources.

The first area reflects a paradigm shift during the last decade with the emergence of ecohydrology as a subdiscipline that explores how Darwinian concepts of competition for water by vegetation can inform our understanding of hydrologic processes. Although vegetation controls on the water cycle (and the intimate linkage of the carbon and water cycle) are central to this theme, understanding the linkage between the hydrosphere and biosphere is also important to biogeochemical cycling of elements because of the close linkage between water and the microbial communities that control processes such as weathering and nutrient transformation. Community support is required to bring the multidisciplinary teams together to make advances in this area.

The second community goal, by contrast, focuses on a process of discovery rather than a specific scientific area. Observations are typically made at plot to catchment scale (from a few square meters to a square kilometer), and mechanisms of hydrologic transport and biogeochemical transformations can be inferred from these observations. Whether these findings can be directly scaled to the watershed or river basin scale (thousands to millions of square kilometers) is an area of active research. Community support in modeling tools, synthesis, and field infrastructure at larger scales is needed.

The final area is the ultimate goal for the hydrologic science community. Achieving this goal requires progress on the first two goals. Community support is required primarily in the modeling area, including data assimilation and benchmarking of current understanding. Liaisons with professional communities from atmospheric sciences, environmental engineering, and ecology are also required for the development of the comprehensive models required to explore this area. Synthesis activities will be required to make progress

Each of these goals is important to society. Although seemingly disparate, progress on each requires a more comprehensive understanding of the hydrologic cycle and its four fundamental properties of stores, fluxes, flowpaths and residence time. For reference in the following discussion, a simplified, one-dimensional schematic of the hydrologic cycle is presented. Four stores are delineated (atmospheric water, surface water, soil water, and groundwater) and the fluxes between them. This simplified view ignores that, in a three-dimensional world, exchanges among these stores occur in both directions, such as a river that can alternate between gaining water from the saturated zone and losing water to the saturated zone depending upon its geologic setting. Thus the flowpaths can be far more complex than are apparent from this diagram. As a result, determining the residence time within a store is also more complicated;

residence time is best considered as a distribution of rather than a single value. Finally, such a diagram ignores that these stores are dynamic, with interfaces between the stores (areas generally of intense biologic activity) changing in time.

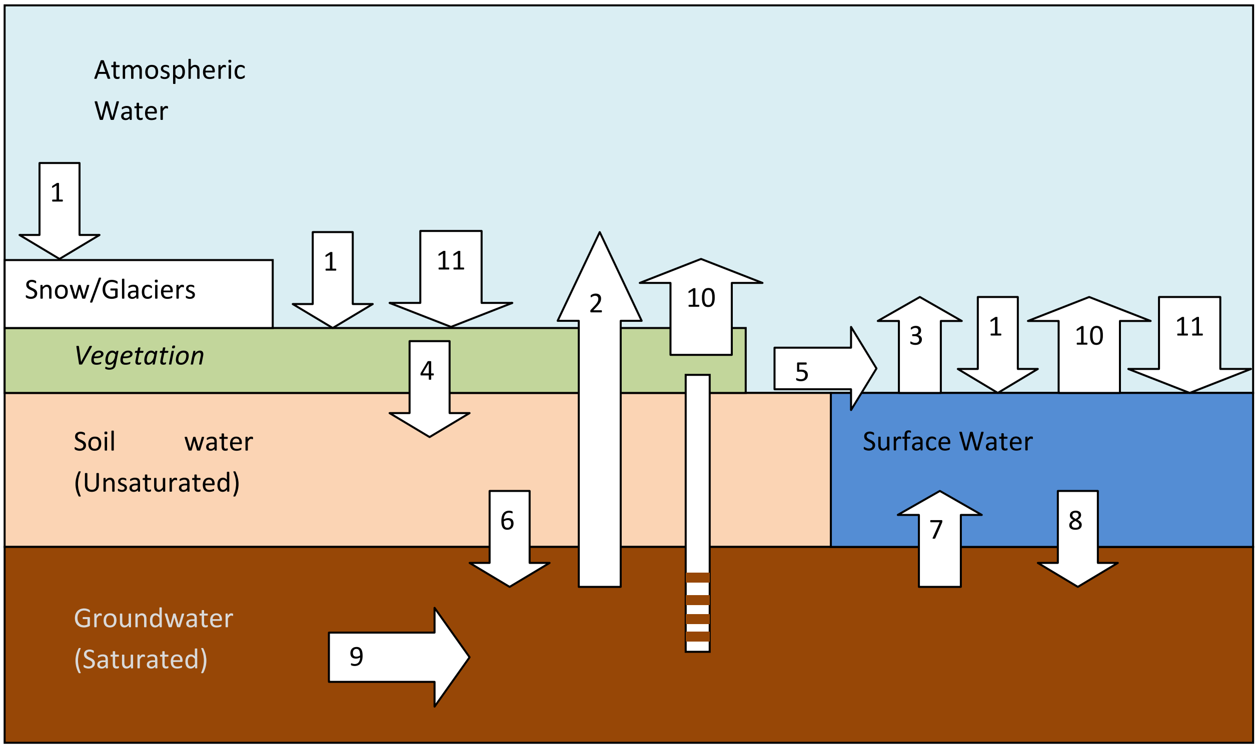


Figure 2. Schematic diagram of the terrestrial hydrologic cycle. Five major stores of water are shown: atmospheric water, snow and glaciers, surface water (e.g., lakes and rivers), soil water and groundwater. These stores are linked by 9 major fluxes: 1. *Precipitation*, 2. *Transpiration* through vegetation, 3. *Evaporation* from free water surfaces, 4. *Infiltration* from the land surface to the unsaturated zone, 5. *Runoff* from land surface to surface water, primarily from unvegetated, impervious surfaces, 6. *Recharge* of groundwater from unsaturated zone, 7. *Discharge* of groundwater to surface water, 8. *Recharge* of groundwater from surface water, 9.*Transport* of groundwater down gradient within or between aquifers, 10.*Human withdrawals*, such as groundwater pumping, and 11. *Human return flows,* such as irrigation, and sewage discharge.

2.1 Linking the Hydrosphere and Biosphere

The representation of vegetation simply responding to rainfall has given way to an appreciation of dynamic interaction among climate, soil, and water (Rodriguez-Iturbe, 2000). The field of ecohydrology has emerged, defined by Newman et al (2006) as a discipline that seeks “to elucidate (1) how hydrological processes influence the distribution, structure, function, and dynamics of biological communities and (2) how feedbacks from biological communities affect the water cycle.” Newman et al. (2006) further suggest that ecohydrology could lead to a synthesis of Newtonian and Darwinian approaches to science [e.g., Harte, 2002]. Newtonian principles of simplification, ideal systems, and predictive understanding (typically used by hydrologists) can be combined with Darwinian principles of complexity, contingency, and interdependence (typically used by ecologists). Can such a combination lead to a profound and more rapid advance in our understanding of environmental processes? Harte [2002] identifies three “ingredients” for how such a synthesis can be realized: (1) development of simple, falsifiable models, (2) identification of patterns and laws (e.g., scaling laws), and (3) embracing the science of place.

The soil-water store (Figure 2) figures prominently in the linkage between the hydrosphere and biosphere as it mediates between transpiration and recharge and is a key factor in soil-forming processes (pedogenesis). Yet, this store of water is the most poorly measured in the hydrologic cycle.

Where water is limiting in arid and semi-arid environments, the feedbacks between the biosphere and the atmosphere are expected to be strong. See sidebar by Newman (2006). Perhaps more unexpectedly, Gupta and colleagues have found that riparian vegetation in the Whitewater River (KS) has a systematic effect of reducing flood peaks in a stream network that was not predicted from physical considerations alone (personal communication, V.K. Gupta).

Example questions that emerge in linking the biosphere and hydrosphere are:

How does the biosphere mediate the interaction between the slower sub-surface moisture dynamics and faster above-surface atmospheric dynamics?

What controls the partitioning of precipitation between recharge, runoff, and evapotranspiration, and how does this control differ with environment and scale?

What are the spatial patterns and temporal variability of snowpack, soil moisture and vegetation, and how do they respond to and/or control patterns of precipitation, recharge, runoff, and evapotranspiration (and groundwater flow, geomorphology, biogeochemistry)?

Can the structure of porous media in the rooting zone be predicted as competing physical processes, where a self-organizing system of pores develop to drain water as quickly as possible and ecological processes where vegetation seeks to maximize carbon production by maintaining a mesic environment?

2.2 Upscaling hydrologic, biogeochemical, and geomorphic processes

Hydrologic science seeks physically based “laws” that will have wide applicability and high predictive power. Traditionally, hydrology has applied findings from fluid mechanics, together with the necessary constitutive relations to develop sets of governing equations, much the same as atmospheric and ocean sciences have done. However, because the solid earth is not a continuous fluid, hydrologic science has had to contend with heterogeneities in porous media, in surface roughness or in channel geometries. Typically, these heterogeneities have been captured in so-called ‘effective’ parameters, which are determined by calibration of the model.

In biogeochemistry and geomorphology, similar approaches have been adopted, such as the application of thermodynamics to the chemistry of natural waters, and mechanics to sediment particle interactions. In each case, a highly idealized representation of the natural system is necessary to construct governing equations.

With advances in computing power and in instrumentation, we have the ability for developing computer models and to collect data with greater spatial and temporal resolution than ever before. Two competing approaches have emerged in the hydrologic science community. The first seeks to use these advances to directly upscale the current governing equations to larger areas using, for example, finer finite element meshes or cellular automata techniques. The second approach identifies patterns at the catchment or watershed scale and seeks to understand how these patterns arise (Sivapalan, 2003; Kirchner et al., 2001). Organizing principles are sought that seek to understand how heterogeneities arise rather than attempting to measure them. Flood scaling is an example of this second approach (see sidebar).

Example questions in this community goal are

How do spatial patterns and temporal variability of different physical, chemical and biological processes link up to create stream networks and subsurface flow pathways, and what new processes emerge from this watershed network?

Over what time and space scales, and during what seasons, are macropores and other short-circuit pathways dominant, and what is the role of disturbance in these pathways?

How do spatially organized patterns of vegetation, such as biomes, emerge as a result of feedback between sub-surface and atmospheric water dynamics and will they change under changing climate?

How does vegetation interact with the hydrologic cycle in arid and semi-arid environments?

Adapted from Newman et al (2006).

The distribution, growth, and mortality of vegetation are more sensitive to the hydrologic cycle than to any other factor (e.g. nutrients, sunlight) on a global average. The growth and biomass accumulation of vegetation is strongly correlated with total annual precipitation (Knapp and Smith, 2001; Waring and Running, 1998). In the Southwest, seasonality of precipitation input is also critically important because the monsoon precipitation typically arrives in mid-summer; a time of relatively hot weather that can support high growth rates, but can also cause temperature stress and significant cavitation and subsequent mortality if a drought occurs. Such seasonality has dramatic impacts on vegetation (Fernandez-Illescas and Rodriguez-Iturbe, 2004; Schwinning and Ehleringer, 2001; Huxman et al., 2004; Smith et al., 2000) of arid and semiarid ecosystems. The current drought is already showing dramatic effects on the vegetation; the current mortality of piñon and ponderosa pine is widespread throughout Utah, Colorado, New Mexico and Arizona. In contrast, vegetation along riparian corridors is historically accustomed to flooding as a source of nutrients and water. Such flooding has been minimized through engineering efforts to control river flows. Overall, direct anthropogenic manipulations of river flows along with indirect alteration of the climate that shifts the timing, frequency, and magnitude of precipitation are likely to have profound impacts on vegetation survival and productivity in this region where vegetation is already coping with minimal water availability.

Predicting vegetation response to changes in the hydrologic regime requires models based on first principles of plant carbon-water balance (Landsberg and Waring, 1997; Running and Coughlan, 1988; Williams et al. 1996). Understanding the response of plant carbon gain (photosynthesis) to water availability is necessary because plant productivity and survival are dependent on carbon acquisition. We have detailed understanding of whole-plant transpiration (Granier, 1987) based on continuous sapflow measurements, on plant thresholds for xylem cavitation (Holbrook and Zwieniecki, 1999; Sperry et al., 2002; Tyree and Sperry, 1988) based on branch-level conductivity measurements, and on stomatal regulation of transpiration (Bond and Kavanaugh, 1999; Cowan, 1977; Jarvis and Morison, 1981; Oren et al., 1999) from leaf-level measurements. This work has identified some fundamental mechanisms by which plants regulate water loss, mechanisms which are commonly incorporated into ecosystem process models. However, technology to measure the response of carbon gain to hydrologic variation has lagged behind water flux measurements.

Stable carbon isotope ratios of plant organic matter have demonstrated species adaptation to water availability over the lifespan of plants (Ehleringer et al., 1993). On shorter timescales, eddy covariance measurements of ecosystem carbon exchange are now allowing us to determine the short-term (daily) response to water pulses (Huxman et al., 2004). Ecosystem-scale stable isotope measurements are now showing regional and temporal response of ecosystem water use efficiency to water availability (Bowling et al., 2002; McDowell et al., 2004). Incorporating this knowledge into an ecohydrological framework is essential for predicting vegetation response to changes in water inputs and for predicting how vegetation will affect water fluxes and water storage. At larger scales, changes in species abundance and composition resulting from climatic fluctuation and disturbance must be taken into account (Neilson and Marks, 1994; Neilson, 1995). Measurements at this scale have truly lagged behind the models. However, new technologies (e.g., advances in satellite remote sensing capabilities) show promise for improving our ability to quantify biogeographic responses to changes in the hydrologic cycle. Understanding the carbon balance response of terrestrial ecosystems to changes in the hydrologic cycle is essential for future prediction of terrestrial carbon sequestration under various climate change scenarios (IPCC, 2001).

The effect of network topology and channel-floodplain morphology on the scaling of floods, sediment and nutrient fluxes, and ecosystem dynamics (after Paola et al., 2006)

Scaling of floods has been the subject of considerable research in hydrology starting with the simple normalization methods, e.g., the index flood method, to the recent statistical multiscaling theories [*Gupta et al.*, 1994]. A key question concerns the variation of flood intensity and frequency with the drainage area of the basin (scale). Analysis of observations from several regions has supported the inference that floods exhibit a multiscaling structure (i.e. the statistical moments scale as power laws with drainage area with an exponent that depends nonlinearly on the order of the moment) with a scaling break at a characteristic scale. Although such an approach yields a concise statistical model which can be useful for regional flood quantile estimation of design events, a number of open questions remain. For example, what is the physical origin of the observed scaling and what determines the scale of the break? What is the relative role of space-time precipitation variability versus geomorphologic controls, e.g., systematic variability of hydraulic geometry with scale and dynamic channel-floodplain interactions, in determining the scaling of floods and streamflow hydrographs [*Dodov and Foufoula-Georgiou*, 2004; , 2005; *Menadbe and Sivapalan*, 2001]? Bringing sediment into the picture, what controls the size distribution of sediments produced and delivered to channel networks by hillslopes? How are the size distribution and flux rates of bed material affected by the drainage network structure? And how does bedload sediment flux relative to available discharge drive the dynamic evolution of the drainage network structure itself?

Recent research has shed new light on how the spatial structure of ecosystems interacts with the spatial structure of the landscape [*Caylor et al.*, 2005; *Caylor et al.*, 2004; *Porporato et al.*, 2004; *Porporato and Rodriguez-Iturbe*, 2002]. Channel networks provide an organizing template for the ecohydrological and biogeochemical interactions that determine the vegetation patterns and ecosystem dynamics in a river basin. Important questions remain to be answered: What are the feedbacks between flow regime and dynamics of riparian vegetation? What is the relative role of large-scale determinants of vegetation patterns, e.g., optimal response to water stress, and smaller-scale controls mediated by the network structure? What is the relative role of space-time rainfall variability versus channel network topology in determining the spatial patterns and dynamics of vegetation? How does the physical structure of the landscape influence habitat quality and diversity, and how does it control sources and flows of organisms and limiting nutrients [*Power et al.*, 2005; *Power et al.*, 1995]? In turn, how do organisms shape the landscape through microbial weathering, the stirring and diffusion of soil, flow baffling and the stabilization of bars, banks and floodplains [*Dietrich and Perron, 2006*]? What are the coupled dynamics of hillslope-floodplain-stream interactions and what is their role in biogeochemical cycling [*Green et al.*, 2005]?

2.3 Predicting the Effects of Human Development and Climate Change on Water Resources

Human development and predicted climate change may force the continental environment into conditions that have not been experienced before. An integrated understanding of continental water dynamics is required to convert a prediction of an *n* degree increase in temperature into a prediction of the effects of such an increase on water resources and vegetation communities. Will agriculture still be feasible? How will an increase in severe events impact the hydrologic cycle? As populations shift to coastal and arid areas, water resources become stressed. What is the hydrologic "carrying capacity" of a river basin and what are the ecological, economic, and social trade-offs for providing water to a growing population?

Challenges also exist at shorter time scales. Wood and Lettenmaier (2006) note that seasonal river forecasting in the West has not improved since the 1960's due to a combination of greater climate variability and the inability for operational forecasting techniques to incorporate new sources of data, such as satellite observations of the extent of snow cover. Current operational models are based upon regression equations that assume a static relationship between climatic and hydrologic independent variables and predicted stream discharge. These models can't incorporate that these relationship are apparently changing. Different approaches, such as ensemble streamflow predictions, a form of data assimilation, are needed.

Sample questions in this area include

How does human development change the partitioning of precipitation, the behavior of drainage networks, the pathways for subsurface flow, and the movement of pollutants and how does this differ with environment and scale?

How will climate change alter the pattern, variability, type, and intensity of precipitation, and what effect will it have on partitioning of precipitation at the land surface and on watershed response?

Will continued human development couple with climate change to modify patterns and amplify variability, especially the propensity for rare or episodic events like major floods and droughts?

3. Implementation Plan

These and other questions, and the severity, complexity and scale of water-related issues facing the nation today, requires a more structured approach to advance our understanding of Continental Water Dynamics than we have at present. New observations, informatics, instrumentation, and synthesis will be combined in a three-step approach, beginning with benchmarking current understanding, followed by cross-site comparison and culminating in long-term studies.

Phase 1. Benchmarking Current Understanding and Prototyping New Observational Systems (2008-2012)

To achieve community goals, we must both engage in synthesis activities and continue to progress on observational and informatics goals. CUAHSI strongly supports continuation of the development and testing of prototype observatories, both as stand-alone facilities and through partnerships with other observatory initiatives within NSF. By way of synthesis, CUAHSI envisions a series of workshops, organized by science goal and subdiscipline within hydrologic science, that presents the state of the science and prepares quantitative benchmarks that can be used to measure progress. Accomplishing this effort will require informatics support.

Observations. Considerable effort is underway across the hydrologic community in the U.S. and elsewhere to build both virtual and prototype real observatories that will provide the short- and long-term measurements that are absolutely critical for advances in the field. This building of on-the-ground observatories, which have ground-based instruments linked with satellite and other remotely sensed data, is beginning to occur despite the lack of an organized hydrologic observatory program. Hydrologists are actively involved in planning for a WATERS observatory initiative, and have contributed to planning the NEON observational network. During this phase, CUAHSI will engage in two main activities. First, it will continue to support development of prototype and collaborative observatory networks, with e.g. with WATERS, NEON and CZO. Although these will not in themselves constitute a hydrologic observatory program, they will provide valuable community data for synthesis and planning, as well as hypothesis testing. Second, it will initiate benchmarking of these prototype observatories, along with long-term other long-term facilities with a hydrologic component, e.g. USGS and ARS experimental watersheds, LTER sites.

***Informatics*.** The CUAHSI Hydrologic Information System promises to streamline access to data from multiple government and academic providers. This effort to date has focused on simply time-series data collected at a point. Assembling data from just a few agencies has shown the breadth of monitoring activities that contribute to our understanding of continental water dynamics (Figure 3).

Although this map includes a subset of points where measurements are made, and doesn't include dynamic fields, such as precipitation radars, a picture emerges of the *virtual earth* in which data from multiple sources can be displayed in a common geographical framework and be readily accessible for analysis, as shown in Figure 1.

The current HIS project is prototyping the technology for federating multiple sources of point data; this effort will be expanded to consider geographic coverages, and plan for dynamic fields, such as precipitation radar and remotely sensed data.

The CUAHSI HIS team is also committed to serve data specific to the virtual and prototype hydrologic observatories. In many ways this is a greater challenge than the efforts to streamline access to data from government agencies. Support for observatory science will involve managing data at multiple levels, from raw sensor data through processed products. During Phase I the CUAHSI HIS team will build protoypes systems that can be scaled to serve a larger observatory effort.

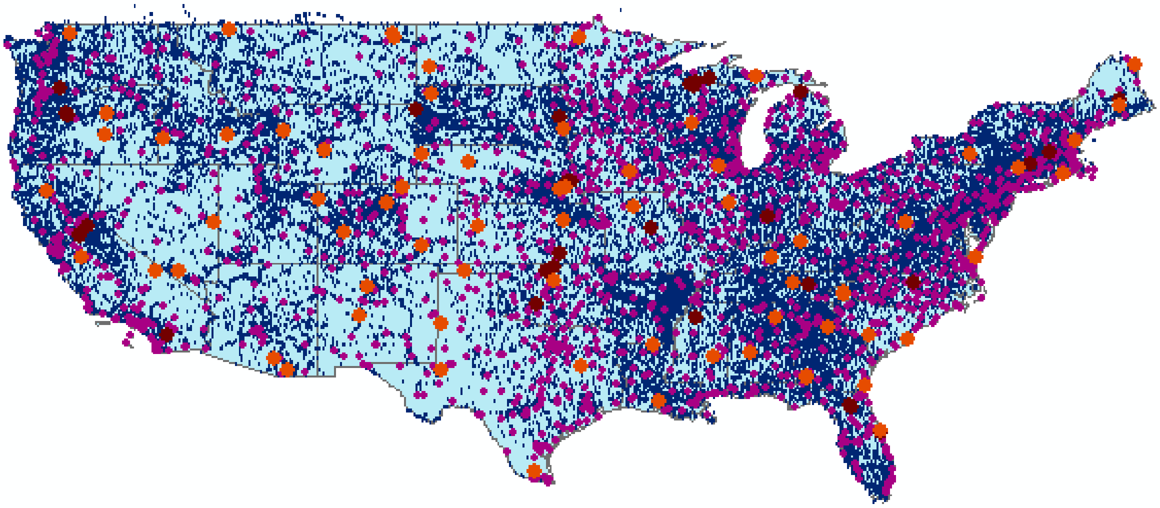


Figure 3. Map showing federation of surface water and groundwater monitoring locations (USGS National Water Information System, small blue dots), climate monitoring stations (NWS-Automated Surface Observing Stations, small magenta dots; and NWS-Climate Reference Stations, large orange dots), and carbon/water vapor sites (Ameriflux, large purple dots).

The current HIS project covers only a portion of the informatics needs of hydrologic science. The virtual earth, mentioned above, can be expanded into three dimensions, as shown in Figure 4. Development and use of 3-dimensional "geovolumes" and "hydrovolumes" will bring together hydrologic, atmospheric, and solid-earth science. Sufficient progress has been made on three-dimensional geographic information system structures to bring this technology to bear on our data.

Activity #1. Development of three-dimensional dynamic virtual earth. This activity will require workshops to scope pilot activities. Many of the enabling technologies are in place and have been evaluated. The creation of virtual earth will permit synthesis among surface-earth disciplines as well as provide a context for many other environmental disciplines.

Assembling the data is one part of informatics needs. A community modeling framework must also be developed to enable better communication among scientists and to improve the efficiency of this effort. Many modeling environmnets have been developed by other disciplines, such as Kepler, D2K and NCSA's CyberIntegrator, that may contribute to this effort. One “workflow” technology developed specifically for hydrologic models by the European Community is OpenMI (http://www.openmi.org), whose conceptual structure is consistent with the data structure adopted by CUAHSI HIS.

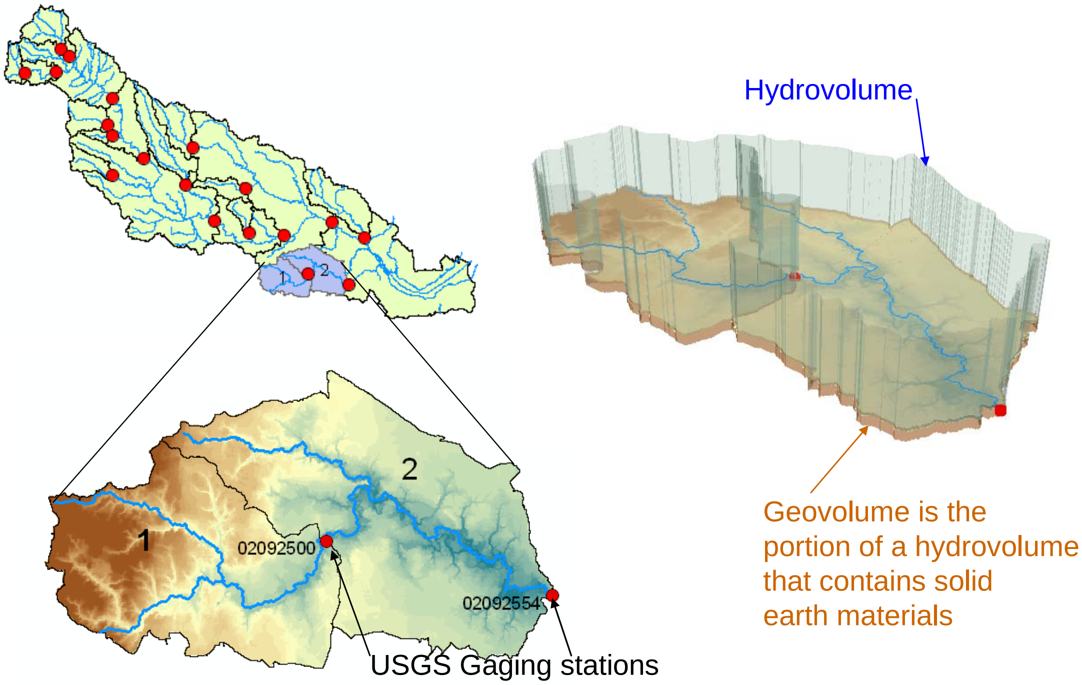


Figure 4. HIS can be expanded to consider three-dimensional data as well as two-dimensional data through geovolumes and hydrovolumes.

Activity #2. Development of Community Modeling Framework. A workshop is required to review potential technologies for establishing a community modeling framework and to scope a pilot project to explore the potential of such a framework for the hydrologic science community.

Activity #3. Simulation models of the integrated hydrologic cycle. A workshop is required to explore alternate approaches to a comprehensive model of the hydrologic cycle that would handle the vastly different dynamics between the atmosphere, and land subsurface and surface environments. This workshop could form the basis for a solicitation for development of multiple comprehensive models that could take place over 2 to 3 years.

Synthesis**.** The informatics activities described above can support a number of observational and synthesis activities that will lead to benchmark development organized around the community science goals. For *Linking the Hydrosphere and Biosphere*, an initial workshop would scope potential synthesis activities for interdisciplinary teams of scientists to pursue that could form the basis for a program solicitation for synthesis activities. For the *Upscaling* goal, workshops would be organized around a range of scales (e.g. plot to catchment, or catchment to watershed) to determine the state of the science and the most effective benchmarks. For the *Prediction* goal, workshops would be organized to assess the ability of the current generation of models to predict system response to climate and human perturbations. Again, progress can be made most effectively by a targeted solicitation for this task.

CUAHSI will also expand its efforts to assess how both historical and future data and information from its sister observational activities noted above can compliment that from hydrologic observatory efforts. This will be an especial challenge given the heterogeneous protocols, data systems and missions of these facilities.

Instrumentation. CUAHSI will work to develop a sustainable model for its hydrologic measurement facility programs, following the plans now in place. At a minimum, efforts will be made to develop a prototype facility

Phase 2. Testing Generality of Understanding (2008-2017)

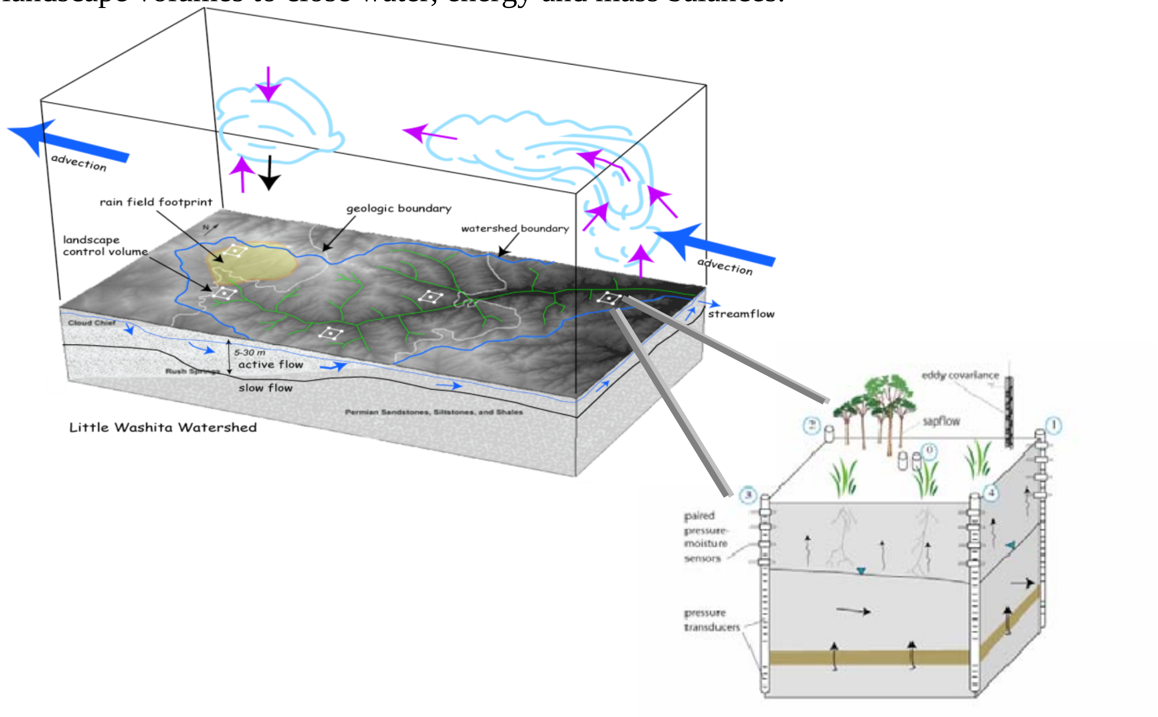
With benchmarks already in place for many sites, hypotheses can be developed to test understanding along gradients represented by multiple sites. The informatics needs for this phase have largely been defined by activities in Phase 1. However, additional measurements and measurement systems will be needed to make meaningful intersite comparisons to test substantive hypotheses. In some cases, sufficient data exist now or will be developed during Phase 1 to move directly to intersite comparisons. These will be presented first as example synthesis activities. A solicitation for intersite comparisons should be developed based upon information gained in Phase 1 to generate proposals for intersite comparisons. Meaningful comparisons must control for obvious differences in climate, soil, and geology to yield scientifically interesting results.

Observations. This phase will feature intensive measurement campaigns of limited duration to test hypotheses. Such campaigns are common in the atmospheric sciences community, but rare in hydrologic science, in part, because an organizing entity such as CUAHSI was only recently founded. Campaigns will build on and compliment the prototype observatory activities. Candidates for place-based “observatories” will be evaluated, first by reconstruction using digital watersheds, and then by a limited duration planned campaign.

Synthesis**.** One example of a topic ready for intersite comparison is the Slope InterComparison Experiment (SLICE), a working group under the International Association of Hydrologic Science’s PUB initiative, where groups from around the world who have instrumented trenched hillslopes are working at comparing results. These studies began with a single design, originating in Japan, that was implemented elsewhere so that comparable data have been collected. Other examples of studies ready for cross-site comparison include Evaporation-Transpiration-Recharge-Snowmelt arrays that have been deployed at many sites around the country. (See sidebar). As with SLICE, ETRS arrays are collecting comparable data around a uniform modeling concept, and, hence, the results are ready for synthesis.

ETRS Arrays. The atmosphere-land-surface-subsurface components of the water cycle represent a complex system of forcings and feedbacks across time scales which range from catastrophic events (flood and drought) to seasonal, interannual and longer time scales of land use and climate change. Understanding the dynamic couplings of soil, ground and surface waters will provide new information and understanding for the efficient development, management and prediction of the nation's surface and groundwater resources.

EvapoTranspiration Recharge Snow (ETRS) arrays are a new generation of sensor platforms that will allow nested observations of bedrock-to-boundary layer at the plot, stream-reach, and hillslope scales organized by landscape control volumes within the watershed unit. The deployment of ETRS arrays in an integrated 3-D domain is illustrated in the first figure. Nesting these observations extends plot scale theory to watershed scale estimation of water, energy and solute balances. ETRS arrays employ turbulence formulation for atmospheric boundary layer processes and Richards/Darcy formulation for subsurface flow. These new generation platforms will provide ground validation for remote sensing land use/landcover data sets as well as provide the basic landscape volumes to close water, energy and mass balances.



Measurement of water, energy and mass flux includes direct estimation of hydraulic conductivity (K) at the plot scale and as a gradient across the hillslope through a nested array, finite element approach. Coherent data to inform the approach is necessary to achieve reliable estimation of flux across the landscape control volume. A viable system of observations will also emphasize the leveraging of in-place instrumentation and access at existing reference sites of federal, state, local and academic institutions.

Contributed by Kevin Dressler and Chris Duffy, PSU

Instrumentation. Historically, intersite comparisons to test hypotheses have been complicated by the lack of comparable data. Access to instrumentation through the CUAHSI Hydrologic Measurement Facility nodes and through the USGS Hydrologic Instrumentation Facility (which has been obtained by CUAHSI for its member universities) will be critical in developing comparable data sets.

Phase 3. Understanding Long-term Response (2012-)

With results from intersite comparisons, we will have gained a more systematic understanding of the factors controlling hydrologic response to human and climate perturbations. The primary motivation for long-term fixed sites is the development of coherent data sets through a range of environmental conditions.

Observations. A national network of hydrologic observatories, on the order of 10,000 to 50,000 km^2 in size, will be established based on Phase 1 and Phase 2 activities. These will complement and in some cases incorporate existing placed-based facilities of sister sciences, like ecology's Long Term Ecological Research and operational agency experimental watersheds of the U.S. Geological Survey, Agricultural Research Service, and Forest Service. Observatories will form continental-scale gradients, and support research involving both pair-wise and broader network comparisons..

Efforts, such as Critical Zone Observatories and test-beds for the proposed WATERS Network, will contribute to our ability to operated these facilities in the community interest. The informatics, instrumentation, and synthesis infrastructure developed during the first two phases will all be needed for the operation of long-term observatories.

It is recognized that the timeline for implementation of this phase will depend on the availability of support through NSF's Major Research Equipment and Facilities Construction (MREFC) program. It is assumed that the earlies date for access to that program is late 2012.

Synthesis. It is expected that a permanent synthesis center will be established under this phase, to continue the community synthesis activities in phases I and II.

Informatics. Major investments in informatics will be needed to scale the prototype systems developed under Phases I and II. It is estimated that perhaps half of any MREFC project would be dedicated to cyberinfrastructure.

Instrumentation. It is expected that a permanent hydrologic measurement facility will be established under this phase, to continue support of community and individual investigator measurement campaigns.

4. Education and Outreach

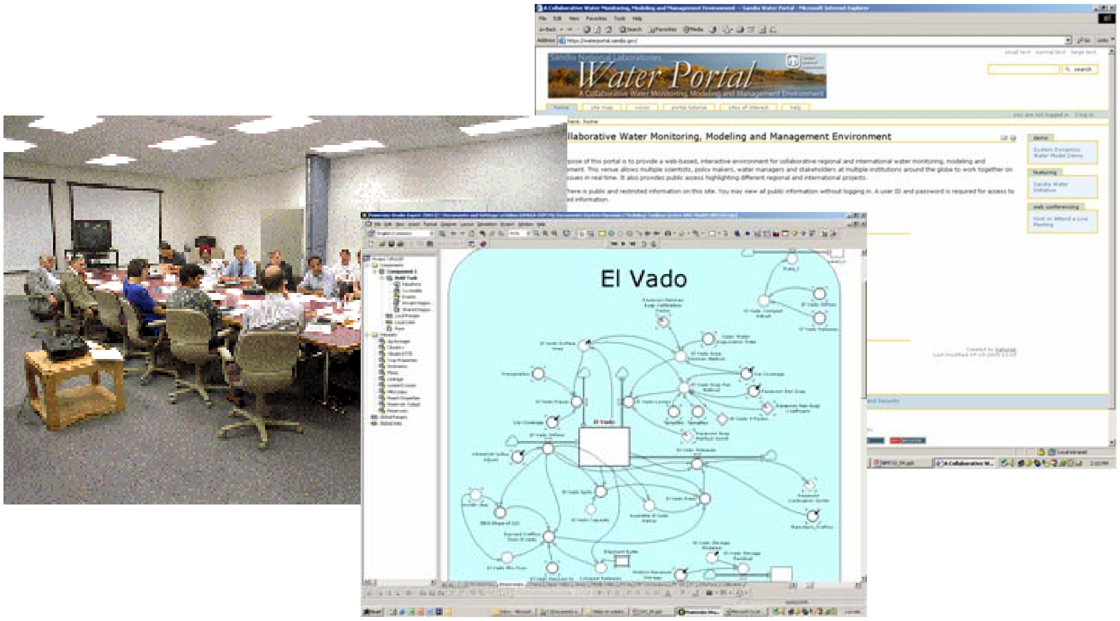
K-12. CUAHSI is developing a hydrologic literacy standard and plans to use it will foster K-12 learning in part through existing relationships among its member institutions. For example, a member institution or watershed-based group would use data and research both to populate instructional modules, focusing on hydrologic science, and to educate instructors regarding activities and data. Instrumentation from the HMF would be used to develop state-of-the-art examples of data collection, processing and hypothesis testing to give students actual experience in doing science. Students would have access to real-time data, research reports and field sites (whenever possible) to participate in ongoing projects as they happen. Using CUAHS data and tools, students will be able to communicate their ideas back to the scientists and the general public through CUAHSI supported web portal and media outlets.

Higher Education. The CUAHSI Synthesis Project will be a unifying connection that facilitates and coordinates interdisciplinary and inter-institutional exchanges of knowledge, and leads to innovative new modes of leaning for hydrologic science. CUAHSI will work through existing self-formed academic groups with the mission to improve the predictive understanding of Continental Water Dynamics so that society can make better choices concerning local, regional, and even global water-related issues. Many of these groups exist and have forged working relationships with federal, state and local agencies. These are leading to information and resource sharing, and to other sources of financial support for research and relatred infrastructure. University courses will also utilize products from the hydrologic observing system. An example is a joint internet course, developed between University of Texas Austin and Utah State University, on Geographic Information Science for water resources that uses existing CUAHSI cyberinfrastructure (HIS data services). CUAHSI Member Universities are currently supporting integrated hydrologic science education through NSF's program on Integrated Graduate Education and Research Training (IGERT). The University of Florida has a program on Water, Wetlands, and Watersheds: Adaptive Management, while the University of Maryland Baltimore County has a new program in Urban Water.

Outreach to scientific community and the public. CUAHSI will encourage and seek partnerships to disseminate hydrologic science information to citizens. Currently, CUAHSI has developed an educational video about watershed-based science and the state of hydrologic science in general. Showcased at the 2006 Fall AGU in San Francisco, constituents of all disciplines were able to view and respond to the piece. Such a video is important for public knowledge at public locations such as museum kiosks, university and mission agency websites, and in state and national parks. Relationships with news outlets, such as National Public Radio, in the form of public service announcements or interviews of hydrologic science researchers and representatives of operational agencies would reach a diverse audience. CUAHSI will also support existing outlets such as Southwest Hydrology magazine, produced by SAHRA (Sustainability of semi-Arid Hydrology and Riparian Areas), the NSF-funded science and technology center at the University of Arizona. Hydrologic observing system information, researcher profiles, data archive sites and others will be shared through this and other publications, for the benefit of the science community and the general public.

Outreach to the decision makers. CUAHSI will also support knowledge transfer to decision-making agencies including operational facilities (e.g. Regional River Forecast Centers and reservoir operators, etc) and government activities such as forest land management. Transfer will occur in two parts. First, the cyberinfrastructure will support an open modeling system that includes the development of decision-support tools and real-time module testing (see Box on Computer Aided Dispute Resolution). The development and testing will be done with user group input and in support of individual user needs. Second, CUAHSI technical staff and those associated with HIS will perform workshops to train management on use of evolving tools. Explicit linkages to decision-making groups will foster a necessary ability to adapt to and manage Continental Water Dynamics.

Computer Aided Dispute Resolution. The watersheds in which we live comprise a complex set of physical and social systems that interact over a range of spatial and temporal scales. These systems are continually evolving in response to changing climatic patterns, land use practices and the increasing intervention of humans. Efficient management of these watersheds defies myopic, piecemeal approaches driven by political whim. Rather, planning benefits from the fusion of knowledge and experience widely distributed across physical and social scientists, engineers, resource managers, decision-makers, stakeholders, and the general public. Ideally, an environment is established that promotes shared learning leading to cooperative and adaptive management. Success requires a process for inclusive and transparent sharing of ideas complemented by tools to structure, quantify, and visualize the collective understanding and data, providing an informed basis of dialogue and exploration. System dynamics provides a unique mathematical framework for integrating the physical and social processes important to watershed management, and for providing an interactive environment for engaging the public.



System dynamics models are predicated on the classical formalisms of physical and social science; albeit, at reduced spatial and temporal resolution. This tradeoff in complexity and thus computational burden, allows real-time analysis over an extended decision space. As with any model, their ultimate value depends on the appropriate synthesis and integration of data, science, and scale. Of particular challenge to these systems models is the coupling and interaction that occurs at the intersection between disparate disciplines and scales of analysis. Exploration of Continental Water Dynamics provides a unique basis for understanding science at the "frontiers". Alternatively, such system models provide the vehicle for informed dialogue and shared learning across the diversity of disciplines engaged in Continental Water Dynamics. Finally, broadly vetted systems models provide a unique basis for communicating Continental Water Dynamics to the public and for placing it in a meaningful context for decision-makers. Contributed by Vincent Tidwell, Sandia National Laboratories.

5. Linkages and Partnerships

Continental Water Dynamics integrates the oceans, land and atmosphere, as well as linking humans and other biota to their environment. As such, advancements in hydrologic science benefit other disciplines and hydrologic science requires other disciplines to make progress.

Water and the Critical Zone. Water is both a transport vector for solutes and sediments, as well as a solvent. Because continental water dynamics concerns the fluxes, stores and residence times of water and transported constituents in soil, streams, lakes and aquifers, this topic provides the foundation for hydrologic science. Water and the Critical Zone also deals with the dynamic interaction of the water cycle with other physical and chemical aspects of the environment, particularly the climate, the landscape, and even geology. Continental Water Dynamics is driven by larger scale climate signals; through its influence on land surface processes and latent heat fluxes, and delivery of fresh water to the oceans, it in turn influences climate. Continental Water Dynamics responds to the shape of the landscape and stream network pattern, which essentially transforms precipitation into recharge, runoff, other fluxes, and stores; yet the water cycle is a major geomorphological shaper of that landscape. Continental Water Dynamics is particularly sensitive to geology, indirectly through the effects of geology on landscape and climate (e.g., due to mountain building and related mountain rain shadows), and directly through the effects of subsurface geological heterogeneity on groundwater and related chemical movement; geology is sensitive to the water cycle, for example due to glaciation or, on much shorter time scales, due to the development of caves and karst. CUAHSI’s main science partners in addressing these issues are atmospheric and ocean sciences, and other Earth-surface sciences, including, geomorphology, weathering and soil science, and abiotic aspects of limnology. Agency partners include the U.S. Geological Survey, NOAA, and NASA.

Water and Ecology. Water plays a fundamental role in sustaining plant and animal life in terrestrial, riparian, and aquatic environments, and in turn it also deals with their influences on Continental Water Dynamics. Ecosystem function and health are profoundly affected by the space-time dynamics of water and transported constituents. Terrestrial and riparian vegetation respond to the space-time variation of soil and atmospheric moisture, but they also play a critical function in water cycle dynamics, controlling the temporal and spatial variations of soil moisture, evapotranspiration, recharge, runoff, and even groundwater. Persistent patchiness and hot spots of aquatic life and biogeochemical processes suggest an important but unexplained role for fluid flow, in some cases apparently due to episodic turbulent events, while in other cases gradients are preserved despite observed turbulence. Water’s role in ecology also includes the dynamic interaction of vegetation, aquatic life, and water with other physical and chemical aspects of the environment, particularly the landscape and climate. Vegetation utilizes nutrients and modifies soil, affecting the nutrient cycle and soil weathering, and shaping the landscape from hillslope to basin and continental scales. Vegetation also affects the land-surface energy balance, influences the atmospheric boundary layer, recycles atmospheric moisture, and sequesters carbon. Small lakes and wetlands also store carbon dioxide, that can be released to the atmosphere when atmospheric or water dynamics change, with implications for climate impacts if the release occurs on a regional scale. CUAHSI's main science partners in addressing these issues are ecology and limnology. Agency partners include U.S. Geological Survey, NOAA, NASA, and the Department of Agriculture.

Water and Humans. There is a highly dynamic relationship of water and people. Ten-thousand years ago water played a central role in the development of agriculture and the explosion of human civilization, and now it is essential to the sustainability of a modern industrialized America. As recent disasters remind us, water is not always beneficial to civilization; it is often the most destructive vector of natural disasters. It's also not a one-way transaction. How water circulates, where it is stored, and what quality it takes are continuously stressed and engineered by people. CUAHSI's main science partner in addressing these issues is the engineering community, with whom CUAHSI is designing the proposed WATERS network. Agency partners include the Environmental Protection Agency, the Agriculture Research Service, the Forest Service, and NOAA.

Environmental Science Partnerships CUAHSI will strengthen links to other sciences by working closely with other NSF-sponsored and complementary environmental observing-system initiatives, such as ecology's NEON, and geoscience's other Earth-surface science initiatives in geomorphology and weathering science. Like the hydrologic observing system, each of these other environmental observing systems integrates across disciplines, promotes important new measurements, deploys modern sensor technology, and employs cyberinfrastructure to synthesize data and models. Water plays an important role in all of these other environments, each of which also feedbacks to Continental Water Dynamics. All share similar attributes, including sensitivity to episodic and rare events, significance of spatial patterns, heterogeneity, and gradients in the landscape, importance of scaling leading to thresholds and emergent behavior, and predictive uncertainty and limits of predictability. With these shared attributes, hydrologic and other environmental observing-system initiatives can develop and implement joint-infrastructure components, while coherently pursuing separate but complementary science objectives. Working together yields not only financial and scientific economies of scale, but also connects communities intellectually and operationally so that together they can address even more complex scientific issues than the individual communities have yet imagined.

6. Why Now?

There are three arguments for why now is the time for hydrologic science to pursue a community-based observing strategy.

The community is ready. Hydrologic science first organized as an interdisciplinary effort only fifteen years ago. Since then the community has grown enormously in size and the science made remarkable advances along several narrow fronts, but progress toward the original interdisciplinary vision was slow and fragmented. Progress was also out of balance with that in sister sciences, especially ecological, atmospheric and ocean sciences, who find connections to Continental Water Dynamics to be increasingly important for understanding their portions of the Earth system. The hydrologic-science community has matured and is ready to become truly interdisciplinary. Hydrologic science is now challenging traditional boundaries within its own research and reaching out to these sister sciences, as evidenced by the growth of new fields such as ecohydrology and hydrometeorology. Building on the legacy of past successes, hydrologic science is ready to broaden research agendas, coordinate observations across disciplines and locations, employ coherent protocols, provide strategies for integration of data and models, develop consistent theory and language, and implement a thriving interdisciplinary knowledge transfer.

The science is ready and the science is needed. Hydrologic science has evolved to the point where its disparate parts can now be brought together to focus on specific questions, places and times, to improve predictive understanding. In this context water is the unifying link within environmental sciences and between them and the social and behavioral sciences. There are unpredicted and sometimes abrupt changes to continental water-related systems, coupled to changes in climate and landscapes, ecological systems, and populations, and that past approaches to predictions and problem solving are no longer adequate. Both reductionist and emerging behavior approaches to hydrologic science offer insights and predictive ability, and that research can best be advanced when these two approaches are used to complement each other.

In the last ten years, numerous reports from the National Research Council (NRC), US. Global Change Research Program (USGCRP), the National Science Foundation (NSF), and a long list of professional organizations and consortia, call for a focus on water-related research. For example, enhancing the ability to "predict changes in freshwater resources and the environment caused by floods, droughts, sedimentation and contamination in the context of growing water demand" was identified as one of four grand challenges in environmental sciences by the NRC (2001). The USGCRP's Water Cycle Study Group's *Plan for a New Science Initiative on the Global Water Cycle* (2001) asserts, "despite impressive advances in the models of the Earth system, processes central to the global water cycle are still poorly understood," and, "clearly, data must be developed to support better management decisions and improve model predictions of water cycle variations". More recently, NSF's Advisory Committee on Environmental Research and Education (2005) called for integrated, multidisciplinary, and multi-scale water-related research to meet the challenge of ensuring “an adequate quantity and quality of freshwater for sustaining all forms of life” in the presence of “continued human population growth and the uncertain impacts of environmental change.”

The technology is ready. The advance of computational, data analysis and visualization tools (including GIS, object-oriented modeling approaches and the vast increase in computing power), coupled with new sensors and data acquisition technology, enables the collection, processing, and modeling of data that was inconceivable as little as five years ago. However, the prospect of an individual scientist mastering the broad range of disciplines and their allied data collection and interpretation techniques is daunting. A more practical and productive approach to addressing these opportunities is the development of common programs and infrastructure to be shared by the hydrologic science community.

The future. The intellectual depth and rigor of hydrologic science, as well as its breadth, will grow with the shift from research limited to individuals and small collaborations, to community based and supported interdisciplinary efforts. Once the subdisciplines within the field work together on regular basis, what they learn from each other will lead to significant new insights and a new series of questions and hypotheses, and a further enhancement of the nation’s scientific ability to understand and grapple with continental water dynamics.

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