The CUAHSI Plan for a Network of Hydrologic Observatories

Lawrence Band, Marshall Moss, Fred Ogden

Abstract

The Consortium of Universities for the Advancement of Hydrologic Science (CUAHSI) was founded in 2001 to address and facilitate the study of critical interdisciplinary science issues identified by the hydrologic community (www.cuahsi.org). These include predictability of hydrologic processes, scaling principles and critical interfaces with atmospheric, ecological, biogeochemical and societal processes. A major impediment to this study is the lack of an adequate observational base, and the infrastructure required to acquire this base in watersheds of sufficient size. Hydrologic Observatories (HO) are one of the center pieces of the CUAHSI initiative and are conceived to directly address this gap. They are conceived as major research facilities that will be available to the full hydrologic community to facilitate comprehensive, cross-disciplinary and multi-scale measurements necessary to address the current and next generation of critical hydrologic science and management issues. Some of the topical aspects of the HO mission have been implemented in the form of a subset of the more hydrologically oriented LTER sites, the ARS and WEB experimental watersheds, and through the long term monitoring program of the USGS. However, these efforts have either not been at the scales envisioned for the HO (e.g. 10^4-10^5 km^2), have not emphasized long term measurement, or have not addressed the development of a comprehensive, multidisciplinary information base designed to address the driving scientific and management questions posed by CUAHSI. However, the HO can be designed to build on and integrate these ongoing efforts by identifying larger basins that contain longer term LTER, ARS or WEB sites, or implement more comprehensive, multidisciplinary data collection and experimentation schemes in monitored basins.

Keywords: CUAHSI, Hydrologic Observatories, hydrologic infrastructure

Introduction

Environmental change affects hydrologic systems in ways that cannot be predicted with current knowledge and information, and that pose threats to the future of water supply, water quality, ecosystem health, sustainable use and human society. Environmental changes occurring on scales from local to global include land cover change, climate change, engineered modifications of the hydrologic cycle (e.g., large-scale water transfer or flowpath modification), alteration of biogeochemical cycles, and loss of biodiversity. These changes are superimposed on a background of natural variability, challenging our ability to forecast hydrologic events or differentiate human caused changes. One of CUAHSI's goals is to address cross-scale and interdisciplinary questions that need to be answered so society can anticipate and be prepared to deal with changes in hydrologic systems. A significantly increased investment in hydrologic observation and synthesis is needed to answer key scientific questions that cannot currently be answered with our existing research framework and infrastructure.

A national system (network) of HOs are proposed to provide spatially and temporally coordinated

Band is Voit Gilmore Distinguished Professor, Department of Geography, University of North Carolina, Chapel Hill, NC 27599. E-mail: lband@email.unc.edu. Moss is the past Executive Director of CUAHSI. Ogden is an Associate Professor, Department of Civil and Environmental Engineering, University of Connecticut, Storrs, CT 06269.

interdisciplinary data and infrastructure platforms for research at a new, higher level of integration. Furthermore, in light of continuous and accelerating environmental change in Earth systems, all of the HOs are to collect long-term observations on both a minimum common set of core variables, as well as state and flux variables that may be more locally or regionally important (e.g. permafrost extent, stormwater infrastructure) required to develop mass budgets in water, sediment, and biogeochemicals and trends in these budgets. Long-term observation allows separation of directional trends from year-to-year variability, discovery of thresholds or extreme events that result in surprises, and incorporates a larger number of extreme events. Equally important is spatial nesting that will allow scientific questions to be answered at multiple scales but also, importantly, investigations of scaling phenomena.

The HO network eventually will comprise a set of instrumented watersheds, spatially distributed to cover representative hydrologic regions or ecoregions. Coordination among nodes within the network will be facilitated with the CUAHSI Measurement Technology facility, the Hydrological Information System, and a national hydrologic synthesis center (www.cuahsi.org). Finally, all observatories will implement education and outreach activities and maintain close interaction with local and regional stakeholders.

The HO must be maintained as a community effort, and it will collaborate and coordinate with other appropriate observation networks (including existing hydrologic monitoring). In summary, the HO network will be a sophisticated research infrastructure to support state-of-the-art research in hydrologic sciences and related disciplines that address fundamental and critical water resource problems.

Major new infrastructure needs to be developed in support of this agenda and operated as national facilities to support hydrologic data collection, analysis and synthesis in a manner not feasible with current infrastructure. All data and information generated will be available to the full scientific community. The observatories will also be available for use to the full community as a research facility by competitive proposal and will include:

1. Hardware: state-of-the-art and developing field and laboratory instrumentation that can provide measurement, monitoring and analysis of basic stores, fluxes and transformations of water and associated biogeochemical constituents within large watersheds across a spatial/temporal scale spectrum, as well as tracer and isotopic characterization of water source and residence times. This will be coordinated with the CUAHSI Measurement Technology facility.
2. Spatial data infrastructure – coordinated with the CUAHSI Hydrologic Information System (HIS): characterization of the structure of watersheds including high resolution topography, channel network pattern and morphology, soil, aquifer, land use/land cover, and socioeconomic information, as well as facilities to analyze and correlate data of multiple space and time scales and to integrate, manage and disseminate information,
3. The interdisciplinary environment necessary to achieve an intellectual synthesis, coordinated with the CUAHSI Hydrologic Synthesis Center.

The CUAHSI framework

Recent NSF and NRC white papers on the future of hydrology outline a set of science initiatives and questions focusing on variability and predictability in the hydrologic cycle at multiple scales, the coupling of hydrologic processes with atmospheric and ecosystem processes, and interactions of hydrologic systems with human societal activities (NRC 1991, NRC 1999, Gupta et al. 2000, NRC 2001a, USGCRP 2001, NRC 2001b). CUAHSI has built on these points to formulate a major research theme: to develop predictive understanding of the storage, flux, and transformation of water, sediment, and associated chemical and microbiological constituents under both natural and human-altered conditions. One of the primary points made by the NRC reports and that contributed to the formation of CUAHSI was that research in hydrologic science is observation limited and that the universities are unduly constrained by a paucity of infrastructure to support that research. The CUAHSI Science Plan calls for the establishment of a network of Hydrologic Observatories (HO) for the development of critical observational bases to facilitate formulation and testing of hypotheses posed by the interdisciplinary hydrologic science research community. As the next level of hydrologic research that has been identified as necessary to make significant progress on pressing scientific and societal questions is **integrative** the HO network must incorporate the following four major themes outlined in the CUAHSI Science Plan:

- **Coupling** of the water cycle across disciplinary boundaries with ecosystems and atmospheric, biologic, geologic, and social processes
- **Cross scale** relations, from the level of soil pedons to mesoscale atmospheric systems
- **Hydrologic interface** behavior, (Land surface and atmosphere, land surface and groundwater, surface water and groundwater, surface water and land surface, land-atmosphere, saturated-unsaturated zone)
- **Predictability** of hydrologic processes (e.g. flood magnitude, drought onset and duration, contaminant transport and arrival times)

A combination of longer term, lower density monitoring and short term, intensive field campaigns will need to be designed to support the over-arching science questions that unite the CUAHSI infrastructure initiatives. To address large-scale water and material balances within the natural organization imposed on the land surface by river and stream systems, each hydrologic observatory will be developed over a regionally significant river basin. These watersheds will be large enough to address spatial and temporal variability in regional land surface conditions and the feedback and coupling between the land surface and the atmosphere, on the order of 10^4 to 10^5 km^2. This is considered to be the minimum area within which mesoscale features and land/atmosphere feedbacks may be discerned and tracked. In addition, the recent launch of the Earth Observing System (EOS) generation of satellites include significant global scale monitoring systems with resolutions of 1 km or lower. The scale of the HO will be sufficient to observe and track satellite derived land surface state and flux variables (such as those generated by the MODIS TERRA and AQUA systems), as well as correlate these products with HO generated observations, as well as supporting research in the assimilation of remotely sensed information into regional watershed models.

Each HO will be located in a distinct hydroclimatologic setting, and instrumented with a nested sampling design capable of addressing the order of magnitude variations in the length scales of key processes. These will range from nested observations through the depth of the rooting zone to characterize available soil water dynamics and soil water controls on ecosystem and biogeochemical processes, to regional rain radar, and stream gauge networks capable of generating the information required to study the scaling behavior of flood peaks or low flow patterns.

Instrumentation and facilities in each site needs to be planned to support broad, community defined science questions, as well as to provide base infrastructure required by more specific, individual or group based projects. These latter programs will range from individual Principal Investigator led projects, through the type of large scale intensive field campaigns the scientific community has engaged in (e.g. BOREAS, FIFE, LBA), potentially involving hundreds of scientists. The presence of the HO will facilitate and encourage these types of investigations by making available both basin scale information and instrumentation that would otherwise be unavailable to individual or small groups of researchers, and by providing the context and observational background in large watersheds that is currently missing. Close coordination with the CUAHSI Hydrologic Information System (HIS), the Measurement Technology Facility and Hydrologic Synthesis Center will be necessary to build a network capability that both ties together the individual HO into a continental observing and experimentation system, as well as wide distribution of information generated within the HO to the full hydrologic community.

HO Design

Ideally, there would be between ten and twenty observatories in the network phased in over a period of time to allow adaptive growth and evolution of the network. This scale of observation would allow detection of trends, positive and negative correlations between regional trends, and continental-scale hypothesis testing. A common conceptual framework is derived from using a specific set of science questions distilled from the CUAHSI science agenda as design drivers. The driver questions have societal and scientific relevance ranging from local to continental and global levels and the nested network design will permit synthesis of the knowledge derived across this scale range.

The set of program drivers that will guide infrastructure and sampling design are drawn from the major scientific questions posed by the set of NRC reports and refined into CUAHSI themes. Program drivers are not exclusive questions the HO will focus on, but will span the hydrologic continuum and promote integrated intellectual and technical approaches to information generation. In this sense they are meant to be sufficiently broad to be representative of the types of cross disciplinary and cross boundary questions the community has outlined and are likely to pose, noting that the function of these drivers is to guide major infrastructure development. These drivers include, but are not limited to:

1. **Land-surface/atmosphere.** Does water cycling within a basin contribute significantly to the precipitation that falls in the basin, and do these feedbacks intensify wet and dry periods?
2. **Land-surface/groundwater**. How do atmospheric and surficial processes control groundwater recharge and how can this knowledge be used to develop quantitative estimates of recharge at the scale of thousands of square kilometers?
3. **Groundwater/surface water**. How can the exchange of water between the regional aquifer, alluvial aquifer and surface water be quantified and its residence time in each domain estimated, as these properties control many biogeochemical properties and influence aquatic ecosystems?
4. **Hydrologic extremes**. How do human modifications of the local hydrologic system (both directly and indirectly by changing the land surface) influence the likelihood and intensity of drought and floods relative to global climatic phenomena such as ENSO?
5. **Land use effects on biogeochemistry**. How does land cover and use influence the loading, transport and transformation of biogeochemicals in large watersheds?

The design is being led by a team of scientists with expertise in each of the relevant areas of hydrologic science inherent in the design questions. The prototype will frame and resolve design decisions that are required for full implementation, including the administrative and management infrastructure to support professional staff, cooperative agreements with existing experimental watersheds and data collection agencies, and university investigators.

The design team members are soliciting input from the general research community as needed. After the completion of the prototype study, competitive proposal design grant applications will be solicited from existing and developing research consortia, in order for teams to take the prototype design and apply its procedures in other settings with the anticipation of competing for one of the first awards to implement a fully operational hydrologic observatory.

CUAHSI is presently developing a conceptual prototype design on the 14,000 km^2 Neuse River basin in North Carolina. For a set of the drivers, a larger area surrounding the basin may need to be utilized in order to approach sufficient process length scales (e.g. land-atmosphere interactions and precipitation recycling). For the Neuse, the likely area to expand to would be the Pamlico-Albemarle Sound drainage area, which is a NAQWA basin. Other drivers may require smaller, more intensively studied catchments within the watershed.

The Neuse River was chosen for the development of the conceptual design of a hydrologic observatory because of: (1) the leadership and support of the North Carolina Water Resources Research Institute (NCWRRI) and the highly capable participation of many scientists from the hydrologic science community in the Research Triangle; (2) the robust suite of both historic and ongoing hydrologic data collection efforts (by Federal, State, and university scientists), and (3) the fact that the Neuse River Basin contains a variety of conditions that are found in many other regions of the country and is not dominated by one particular set of topographic, pedologic, and climatologic conditions. As mentioned above, the Neuse is located within an existing NAQWA focus watershed and contains a set of smaller, more intensively instrumented catchments (although no LTER, ARS or WEB sites). Ongoing monitoring funded by federal and state agencies is geared towards the study of flood hazard and point and nonpoint source nitrogen loading and export from the basin into the Pamlico-Albemarle Sound complex, the second largest estuary in the country and a vital fish nursery for the Atlantic.

A national design team with strengths in different specialties has been assembled to take primary responsibility for the prototype design, with support from a set of other university and government scientists. The primary design team includes:

- Dr. Ken Reckhow, Duke University and NC-WRRI (water quality); Team Leader
- Dr. Chris Duffy, Penn State (hydroclimatology, saturated-unsaturated zone interactions)
- Dr. Jay Famiglietti, UC-Irvine (atmosphere-land interactions)
- Dr. David Genereux, NC State (groundwater-surface-water interaction)
- Dr. John Helly, UC San Diego (information systems)
- Dr. Witold Krajewski, Iowa (hydrometeorology)
- Dr. Dianne McKnight, Colorado-Boulder (biogeochemistry)
- Dr. Fred Ogden, Connecticut (floods/geomorphology)
- Dr. Bridget Scanlon, University of Texas, TBEG, (infiltration/vadose zone hydrology)
- Dr. Len Shabman, RFF (economics/social science)

It is important to note that the prototype design in the Neuse River Basin is envisioned as a design exercise, and does not indicate that an HO will be established in this basin. A set of other sites around the country will be considered for the implementation phase through competitive proposals.

Interactions with Existing and Proposed Monitoring Programs

The nested observation systems would be planned to operate within the framework of the existing USGS surface water monitoring network, which will provide multi-annual and decadal records for regional watersheds. Sparser sampling has been operated for groundwater levels and sediment, nutrient and contaminant transport in surface and subsurface systems for watersheds of similar size to envisioned HO, with notable programs including the National Water Quality Assessment (NAWQA) (http://water.usgs.gov/nawqa) and the National Stream Quality Accounting Network (NASQAN) (http://water.usgs.gov/nasqan). It is important to note that while the USGS monitoring network will provide important context and potential baseline information to develop the HO, it is designed primarily for purposes of resource characterization. Therefore, the existing USGS surface and groundwater monitoring, while providing significant scientific data resources, are also not (by themselves) designed to respond to the major scientific initiatives envisioned. A similar assessment holds for existing NOAA-NWS monitoring networks.

On the other end of the spectrum, the nested sampling requirement suggests that initiation of an HO as a larger watershed containing an existing experimental watershed site would provide significant leverage for achieving cross-scale synthesis. Some of these sites have been operated for decades, and are often instrumented with high spatial density for measurement of multiple components of the hydrologic cycle. An important component of the HO network will be to develop and improve cooperation among the field and research programs of various agencies and with the academic community. However, most of these sites are well below 100 km^2, such that they would be very useful to incorporate into an HO, but are not of sufficient scale to meet the needs of the science questions posed.

Proposal Design Grants

Lack of experience within the community in operation of these facilities at the envisioned nested space and time scales, with the coordination of observations and experimental measurement between disciplines, and the lack of baseline information for many candidate watersheds suggests six month proposal design grants. While this information may exist for a set of watersheds at the envisioned scales, the proposal design grants would facilitate other proposals and allow better refinement of the operational plans for these facilities, to assemble available data and specify what new monitoring needs to be initiated. This would provide the ability to integrate baseline information for a larger set of watersheds, including land cover, stream flow, groundwater levels and atmospheric information, as well as coordinate appropriate partnerships between universities, government agencies, NGOs and community groups and to define regional versions of the basic science drivers.

Considering science questions focussed on water stores and fluxes, coupled with energy, sediment, nutrient balance and transport at multiple scales, important questions that require resolution are what instrumentation and sampling densities may need to implemented to measure specific state and flux variables in the presence of significant, multiple scale heterogeneity in climate, soils, land use, geomorphology and aquifer conditions. The development of full proposals with realistic cost estimates will require assessment of existing infrastructure within a watershed, estimates of additional infrastructure requirements and costs relative to stated science goals, and potential sources of cost-sharing with other agencies and communities with existing interests in the watershed.

The proposal design grants will be made available to develop the consortia required between universities, state and local government, federal agencies, NGOs and community groups, organize and explore available data and information, and develop appropriate research emphases centered on candidate watersheds.

Summary and Expected Results

The goal of the CUAHSI Hydrologic Observatory network is to provide the observational and experimental basis necessary to approach the set of multiple-scale, interdisciplinary science questions that have been identified by the hydrologic community, with sufficient flexibility to adapt and distribute developing technology in measurement and information science, as well as to identify and address emerging questions within the hydrologic sciences. The successful design and implementation of a Hydrologic Observatory network, in conjunction with the CUAHSI Hydrologic Information system and Measurement Technology Facility will provide the interdisciplinary hydrologic community with enhanced infrastructure required to make substantial progress on critical scientific and policy related questions surrounding current and future distribution, circulation and characteristics of water and its constituents within the hydrologic cycle. As the community has concluded that the current state of our science is observation limited, design and delivery of this infrastructure as community facilities is a key task that CUAHSI has undertaken to provide. The facilities will be available for use by the full hydrologic community by competitive proposal, and all information generated within the HO which makes use of CUAHSI facilities will be publicly available within a specified time period. The HO network will have direct interactions with a set of existing experimental watershed and hydrologic monitoring programs by formal arrangement, by geographic nesting of the HO either within larger monitored watersheds (e.g. NAQWA) or by containing smaller, more intensively monitored catchments (e.g. ARS, LTER). The value-added advantages of the HO network is strongly leveraged with these existing programs, and provides the cross-scale and cross disciplinary facilities currently required for the current and future generation of hydrologic questions and issues, but largely not available to the scientific community, and specifically to the university research community.

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