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CUAHSI
universities allied for water research

HYDROLOGIC OBSERVATORY NETWORK

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OVERVIEW

The establishment and operation of a network of Hydrologic Observatories (HO) is one of the activities required to realize the scientific goals of CUAHSI. The observatory network will encompass a set of regional watersheds, with a research infrastructure developed to provide spatially and temporally coordinated interdisciplinary data sets resulting from hydrological monitoring, experimentation, and characterization. The scientific understanding generated by these facilities will be critical to our ability to effectively respond to pressing hydrologic issues including sustainable freshwater supply and quality; the vulnerability of human society and natural and managed ecosystems to extreme events such as floods and droughts; and our ability to cope with change and increasing variability in the hydrologic cycle. As the next level of hydrologic research necessary to make significant progress on pressing scientific and societal questions is *integrative*, the HO network must incorporate the following four major themes:

1. *coupling* the water cycle with ecosystems and atmospheric, biologic, geologic, and social processes,
2. cross *scale* relations, from the level of soil pedons to mesoscale atmospheric systems,
3. *interface* behavior (e.g., land-atmosphere, saturated-unsaturated zone), and
4. feedbacks between *fast* response components (e.g., surface water) and *slow* response components (e.g., groundwater).

Core data generated by HO staff will be available to the scientific community, quality assured, and documented. Facilities will also be available for individual or team research by competitive proposal. An additional role of the HO will be the documentation and public dissemination of the behavior of a set of well-studied watershed systems in response to natural and human-influenced changes, including climate change, land use development, and water quantity and quality regulatory instruments. The observatories will be designed and operated to furnish information vital to answering the community's major scientific questions and advancing hydrologic theory, instrument technology, and analytical methods. This will provide much-needed case studies required to evaluate and develop integrated watershed management and policy initiatives.

In this document, the term "hydrologic" research is used to refer more broadly to the study of water, the impurities in water (hydrochemical, or water-quality aspects), and its interactions with ecosystems (ecohydrology). That is, the scope of measurements and research at HOs will be driven by biogeochemical and ecohydrological issues as much as by questions in physical hydrology.

HOs in aggregate will constitute a distributed national laboratory for hydrologic research. As such, resources will be deployed at the HOs to stimulate study where hydrologic and biogeochemical understanding of the water cycle is currently most limited. The mission of the HOs is therefore to facilitate hydrologic research by:

- Measuring hydrologic phenomena over broad spatial scales and long temporal periods.
- Creating a legacy of well-designed and documented long-term observations and experiments for use by present and future generations.
- Fostering emergent collaborations among scientists and policy decision-makers from different disciplines and agencies.
- Providing baseline data and short-term process studies for conducting major synthesis and theoretical efforts.
- Providing information for the identification and solution of societal problems. In this regard, each Long-Term Hydrologic Observatories (LTHO) should explore basin partnerships involving scientists, NGOs, public and private resource managers, and other decision-makers.

MOTIVATION FOR A HYDROLOGIC OBSERVATORY NETWORK

Human society relies on hydrologic systems for services that affect ecosystems and human health, including the provision of freshwater, flood protection, hydropower, transportation, sewage and waste disposal, and recreation. Society is currently contributing to and confronting a series of large-scale changes (e.g., land-cover change, climate change, inter-basin water transfer, NPS pollution) that affect hydrologic systems in ways that cannot be adequately predicted with current resources or state-of-the-art science. These changes are superimposed on background natural variability that has important impacts on our ability to forecast hydrologic events or differentiate human caused changes. One of CUAHSI's goals (as well as of several national and international committees) is to address cross-scale and interdisciplinary hydrologic scientific questions so that we can approach these important societal issues.

Key scientific questions that should be addressed by implementing LTHOs include:

1. How will natural and anthropogenic environmental changes (e.g., land-use and climate changes) affect water quality and quantity, ecosystem sustainability, and human population?
2. How will long-term, high-resolution hydrologic data improve management of engineered and natural systems?
3. How can we improve measurements and predictions of water, mass, and energy balances over a range of scales?
4. What are the dominant processes at hydrologic interfaces?
5. What interactions between hydrologic and biological systems affect ecosystem and biogeochemical patterns and hydrologic processes?
6. How can we transfer hydrologic measurements, model parameters, and system behavior across wide ranges of scales?
7. How have documented land-use and cover changes influenced hydrologic and geochemical fluxes?
8. How can we improve the prediction of hydrologic extremes (droughts and floods) at various temporal and spatial scales?

For example, a major scientific and policy question focuses on the interactions of water cycling with ecosystem processes in determining sources, transformations, and export of nitrogen to streams and coastal systems. This problem incorporates significant process scales spanning several orders of magnitude reflecting land-surface emissions; mesoscale atmospheric transport and transformation of nitrogenous compounds; wet (precipitation) and dry deposition to the land and canopy surface; land and subsurface transformations dependent on water content, carbon cycling, and microbial activity; transport within surface and subsurface flowpaths; and riparian-stream channel-hyporheic exchange. Water is a major medium, transport agent, reactant, catalyst, and solvent. Study of the existing set of research headwater catchments could integrate local water-carbon-nutrient interactions but could not incorporate land-atmosphere feedbacks, larger scale groundwater transport, mainstream channel/floodplain/riparian feedbacks, or scaling of the processes to regional watersheds. Therefore, an interdisciplinary framework to measure and understand the space-time distribution and flux of water, nutrients, and carbon at multiple scales and within the context of anthropogenic sinks and sources is required within sufficiently large watersheds. Measurements at HOs must extend over time scales sufficiently long to capture system variability. For some processes that may be weeks or years, for others decades.

COMPONENTS OF THE HYDROLOGIC OBSERVATORIES

Major new infrastructure needs to be developed to address the questions listed in section 1. This infrastructure will be 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.
2. Spatial data infrastructure: characterization of watershed structure, including high-resolution topography; channel network pattern and morphology; and soil, aquifer, land use/land cover, and socioeconomic information.
3. Facilities to analyze and correlate data of multiple spatial and temporal scales and to integrate, manage, and disseminate information,.
4. The interdisciplinary environment necessary to achieve intellectual synthesis.

ROLES OF THE HYDROLOGIC OBSERVATORIES

The scientific objectives we seek to address focus on the water cycle and interactions with surface and groundwater, ecological, atmospheric, geomorphic, and biogeochemical processes within the context of human social and economic systems. A set of major theoretical and methodological themes within the science objectives will determine the nature and structure of the observatories. These themes include linkage of the hydrologic cycle with biological systems; the character and dynamics of interfaces and hydrologic boundaries (land-atmosphere, land surface-groundwater, groundwater-surface water, and land-surface water); the ability to scale measurements and information from local to regional systems; and linkage of the hydrologic cycle with management systems and societal systems. While specific scientific questions will likely evolve over time, these crosscutting themes call for the development of a distributed, long-term research infrastructure with the following major roles:

1. **Observational centers.** Hydrologic Observatories will provide the science community with well-supported platforms and infrastructure essential to carry out spatially and temporally nested monitoring and experimental data generation. These observations will be used to generate information needed to develop new understanding and theory of hydrologic and related processes as well as an empirical base to test hypotheses regarding the dynamics and behavior of integrated watershed systems. Infrastructure will be operated as a network of national facilities, available for use by competitive proposal. In addition, the operation of well-studied sites built around focal questions will provide the community with a scientific need, contextual framework, information, and facilities to develop and test new instrumentation in conjunction with the CUAHSI Measurement Technology Group. Core measurements by the distributed network will provide the ability to pursue comparative research and answer hydrologic questions at regional to national scales.

2. **Synthesis centers.** Hydrologic Observatories will serve as synthesis centers, which are crucial to the goals of integrating an Earth system science perspective on the water cycle. There are at least three levels of integration that an HO requires. First, the role of a synthesis center requires that the monitoring and experimental data collection outlined above be planned and carried out with emphasis on characterizing integrated system behavior, beyond that of individual material or energy cycles. Second, this approach will also facilitate the development of an interdisciplinary scientific paradigm within which interdisciplinary scientists work on common problems, and are provided with the infrastructure and intellectual environment to explore and test integrative theory and operational methods. This will be achieved by combinations of interdisciplinary multi-scientist investigations and working groups, as well as by problem-oriented interdisciplinary workshops. Third, research facilitated by and carried out at HOs needs to build on and integrate ideas from both the scientific and application communities.

3. **Information centers.** Information generated within the HOs must serve the broader needs of the community focusing on the hierarchy of driving questions ranging from fundamental and broadly based scientific issues, to more regionally specific manifestations of these issues that have

specific management and policy implications. In this sense, the observatories need to operate as nodes within a national network that contribute quality assured data and information as quickly as feasible to a centralized information distribution facility. This aspect is imperative to maintain an open data environment in which the observatories serve the broad scientific community and avoid proprietary data issues and to achieve synthesis of information generated by the network of observatories. This will require significant integration of the Information Systems Group with the HOs.

4. **Education and outreach centers.** All of the above roles and initiatives of the HOs will furnish strong, interdisciplinary educational facilities for undergraduate and graduate training, K-12 outreach, and public participation. As a university-based consortium, each observatory will develop an integrated undergraduate, graduate, and continuing education (operational hydrologists, policy-makers) curriculum involving interactions between university departments, and the combination of education in advanced theory and methods, with direct, hands-on participation in monitoring and experimentation. HOs should build partnerships with K-12 and other groups that can do volunteer monitoring following established protocols and quality control procedures and using well-documented data management systems (see, for example, www.globe.gov). This high level of integration of science and education engages the broader public in science, improves hydrologic literacy, and provides supplemental data beyond what can be supported with HO resources.

5. **Applications partnerships.** State and local government and interested community groups can be identified at the outset to ensure relevance to watershed residents, complementarity and integration with existing monitoring activities and issues, and smooth field logistics. The integration of stakeholders and scientists in setting the research agenda (see above) leads naturally to a more encompassing end-to-end integration of the research at HOs in a chain that extends from stresses (e.g., hydroclimatic variability, land use changes), through research, to improved decision-making. HOs should aim to build and maintain two-way partnerships with regional stakeholders where research results can have a direct impact on water resources management.

LOGISTICS: WATERSHED AREA, SPATIAL AND TEMPORAL SAMPLING STRATEGY

The interdisciplinary nature of the driving scientific questions suggests that the Hydrologic Observatories be designed with a nested sampling scheme that will operate over multiple temporal and spatial scales, reflecting the disparate scales of hydrologic, ecosystem, and atmospheric processes and feedbacks (Figure 1). In addition, there may be important jurisdictional scales and boundaries embodied in HOs that might impact water demand, water storage and transfers, and land use. A combination of longer-term, lower-density monitoring and short-term, intensive field campaigns will be designed to be responsive to current and developing scientific questions. This will require significant advanced planning, logistical coordination, and a range of spatial and temporal operational domains that are typically absent in more discipline-specific monitoring or experimentation.

In aggregate, the network of HOs will constitute a distributed national laboratory for hydrologic research. We realize that a "one size fits all" approach will not work in a geographically distributed network, so some flexibility in HO size and measurement strategy will be needed. However, a core set of measurements using common protocols and strat-

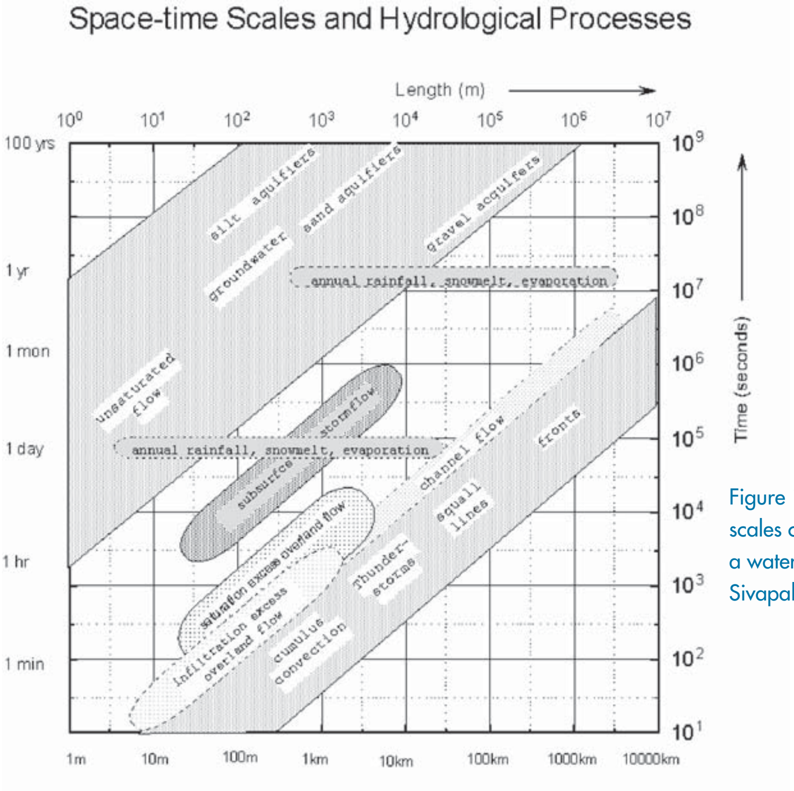


Figure 1. Approximate space-time scales of hydrologic processes within a watershed. Figure adapted from Sivapalan and Bloschl (2000).

egies is required of such a network. HOs should be geographically distributed, and should reflect the diversity of hydroclimatic and ecological regimes in the United States.

SPATIAL SCALES OF MONITORING

The study of land-atmosphere interactions allowing for two-way feedbacks dictates a minimum order of magnitude area over which observations need to be made, while the set of hydrologic-biogeochemical interactions such as occur within riparian areas dictates more intensive monitoring over much smaller spatial extents. At present, it is envisioned that the HOs will cover watershed areas on the order of 10,000 km^2. This is considered the minimum area necessary to observe and represent the horizontal structure of *in situ* and propagating mesoscale atmospheric features and interactions with land-surface processes. Spatial grid increments to analyze these features and interactions should be 10 km at the largest. Note that this total area is specified as an order of magnitude, and an HO may extend an order of magnitude above this limit in well-characterized areas and depending on effective length scales of active processes within a specific environment.

TIME SCALES OF MONITORING

In addition to spatial nesting, temporal nesting of short duration but multi-season intensive field campaigns will be carried out within the context of long-term monitoring. The hydrologic, atmospheric, and ecosystem research communities have gained some experience with short duration field campaigns with nested observations over the past two decades. Field campaigns in hydrology have typically been geared towards the study of land surface-atmosphere-ecosystem interactions, focusing on the fast response components of the system (e.g., energy-water-carbon exchange), while slower components (e.g., groundwater, ecosystem aggradation) may not be addressed. Without these longer-time-scale feedbacks, the complex watershed response may not be adequately captured. Strategies for integrating intensive field campaigns within the framework of long-term monitoring need to be devised to operate over a network of sites, with the campaigns rotating through the network. This temporal nesting requires that the HOs be funded for long-term science monitoring with six- to eight-year renewable terms (subject to sufficient performance and submission of new proposal). This model has been developed within the NSF-Long Term Ecological Research (LTER) network (six-year terms), with examples of sites that have been funded for multiple cycles (in some cases with matching funds from the Forest Service or other agencies), as well as sites that have been discontinued.

MONITORING AND MEASUREMENT METHODS

Novel measurement methods, as well as recently developed techniques still not widely available to the community (e.g., LIDAR topography and atmospheric vapor concentration, high-resolution rain radar, cross-borehole tomography, continuous *in situ* hydrochemical sensors) will be coordinated with the Measurement Technology Group to provide state-of-the-art monitoring and experimental methods and to homogenize methods across the HO national network. More standard monitoring techniques, such as measurement of streamflow, groundwater levels, and head, and the collection and analysis of chemical samples will be the responsibility of the university group managing each HO; to the extent possible this should be coordinated with the USGS (or other federal hydrologic agencies where appropriate —for example, the USDA Forest Service [FS] and Agricultural Research Service [ARS]) to leverage the existing monitoring network and data infrastructure. Remote-sensing methods for estimation of land-surface state will be coordinated with NASA and will comprise a significant effort both to extend estimates of land-surface state and to provide additional calibration and testing of remote-sensing system performance. Robust, spatially distributed data sets will spawn a new generation of hydrologic models; these data sets will be used to both run and evaluate model performance. It is also noted that the recent launch of the MODIS/AQUA platform provides both an important source of hydrologic remote sensing information and a role for the HO network in provision of high-quality and larger area ground measurements of hydrologic state variables.

SOCIAL SCIENCE RESEARCH

Water-resources decisions are made in a multi-stress environment; major stresses include climate variability, land-use change, population growth, economic drivers, and technological change. Human individual and institutional behavior will largely determine the magnitude of many of these stresses and how water resource infrastructures are implemented, maintained, and operated. Major social components that will need to be considered as important drivers and feedbacks include:

- water demand
- municipal wastewater and agricultural return flows
- development and operation of water resources infrastructure, for example, reservoirs and groundwater pumping/recharge systems
- land tenure and management (e.g., conservation planning, BMPs, land-use zoning)
- water law, water rights, and water markets
- regulatory environment

This will require that we incorporate a significant social science research component into the driving HO concept. In addition to the use of standard, readily available, social-demographic and economic information from the Census Bureau, additional information on urban water use, agricultural diversions, and groundwater pumping will be required on an on-going basis. Some of this activity has been institutionalized in NSF through initiatives such as *Water and Watersheds* and *Biocomplexity*, but will require additional work and refinement as well as substantial involvement of the social science directorate at NSF to implement within the frameworks of HO and CUAHSI.

APPLICATIONS PARTNERSHIPS

Given the envisioned size and duration of the HO components, the observatories will operate across scales within regional to local communities, requiring significant interaction with state and local governments, NGOs, and the private sector. It is emphasized that information flow in these interactions is two-way, and not a just case of scientists dispensing knowledge to the public. In many (most) cases, local agencies will have much greater familiarity and knowledge regarding local watershed history and behavior, and it is essential that these groups be considered partners within a collaborative effort.

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 major scientific initiatives envisioned. A similar assessment holds for existing NOAA-NWS monitoring networks.

At 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.

National networks of nested experimental watersheds with locations in most of the major hydro-climatic regions of the United States are operated by USDOI-USGS, the USDA-ARS, and the USDA-FS. Figure 2 shows the distribution of a set of small research watershed sites providing information to J. Jones of Oregon State University for intercomparison of hydrologic behavior as part of a NSF-LTER project. The ARS Experimental Watershed Network consists of 14 locations with over 140 instrumented watershed or subwatersheds. Four of the ARS experimental watersheds have drainage areas greater than 100 km^2 (Walnut Gulch, Arizona - 150 km^2; Reynolds Creek, Idaho - 239 km^2; Little River, Georgia - 334 km^2; and, Little Washita, Oklahoma - 610 km^2).

The NSF-funded LTER network currently has 24 sites in a range of biomes in the United States (including Alaska), Puerto Rico, and the Antarctic. Roughly half of these sites have a focus on small watersheds as a tool for studying mass balance of water and solutes, with the better-known sites with long-term records including Hubbard Brook, Coweeta, HJ Andrews, and Niwot Ridge. This network includes urban and coastal/watershed systems, and forest, agricultural, and arid sites. Flux towers are operating at a set of sites, including the long record at Harvard Forest. An emphasis at most of these sites incorporates coupling between water, energy, carbon, and nutrient cycling. Additional information can be found at (www.lternet.edu).

The USGS Water, Energy, and Biogeochemical Balance (WEBB) network consists of a series of relatively small watersheds in relatively pristine environments. Both the ARS and the FS operate networks with multiple nested instrumented sub-watersheds. These agencies have amassed a considerable knowledge base and observational database of hydrological processes over a wide range of hydro-climatic regions in a number of natural and managed ecosystems. In addition, these agencies have acquired considerable experience in how to successfully operate LTHOs (i.e., experimental watersheds). Much of this experience includes knowledge of personnel development and management and specialized instrumentation development and operation. We feel it is essential that the CUAHSI-HO network build on this experience gained, in some cases, through time consuming (and expensive) trial and error field testing.

The existing experimental watershed facilities operated by the federal agencies can provide a basis for CUAHSI to effectively multiply its investment by building upon very large federal agency investments. Building on and leveraging CUAHSI resources with these existing networks could occur both spatially, by nesting existing agency catchments within larger CUAHSI-HOs, and/or by adding complementary observations not conducted by the agencies to provide a more complete picture of the hydrologic cycle and its interactions with the ecosystem (e.g., adding distributed energy and nutrient flux measurements to an existing network of multi-scale rainfall-runoff measurements). To more rapidly and efficiently advance the hydrologic sciences through the use of HOs, it is strongly advocated that CUAHSI and the federal agencies with hydrologic science programs work hand in hand. An effective partnership between these groups will enable joint planning, collaboration, and goal-setting, and avoid duplication of efforts.

There is the potential for strong synergy with the proposed National Ecological Observation Network (NEON), a parallel NSF initiative. The mission of NEON is to establish and sustain the scientific infrastructure and foster development of the intellectual capital needed to address critical questions about changes in ecological systems, to evaluate the ecological impacts of environmental change, and establish the required observational base to test ecological theory. The objective of the NEON program is to build a fully integrated distributed national network of ecological observatories and to provide the technical means and support personnel to achieve the mission of NEON. A subset of the types of measurements identified in the NEON working documents are in common with measurements that would be required or desired for the HO network. These include meteorological measurement networks patterned after the Oklahoma mesonet system, flux towers, and potentially in-stream parameters.

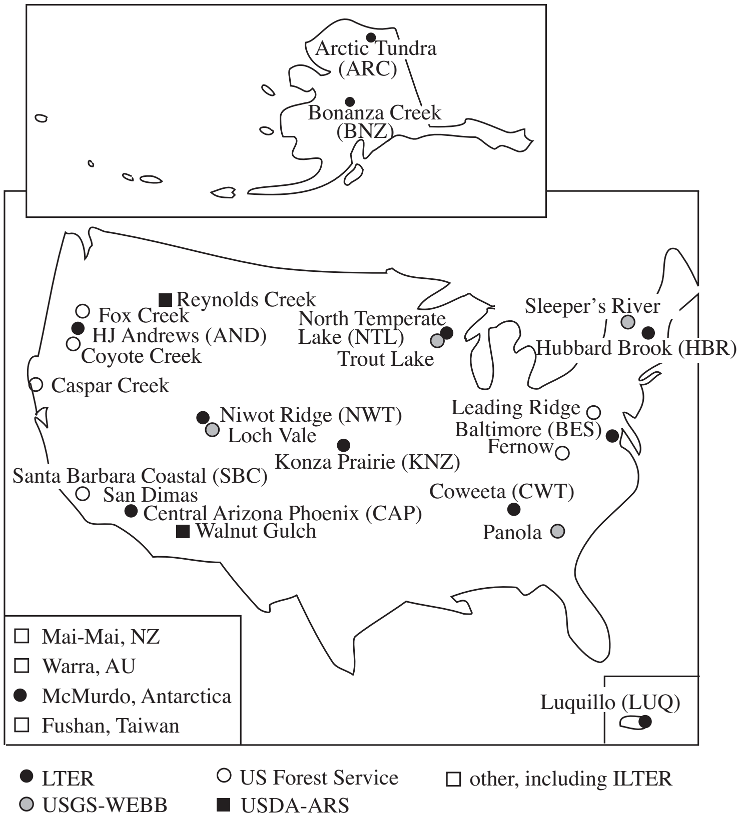


Figure 2. The distribution of a set of small research watershed sites providing information to J. Jones of Oregon State University for intercomparison of hydrologic behavior as part of a NSF-LTER project.

While NEON will not be driven by the same science questions that CUAHSI is posing, and will not necessarily be watershed based, the ecosystem-based observational infrastructure could provide important information for several of our four major themes.

CORE DATA

A fundamental goal of the HO network is to provide a coherent infrastructure for instrumentation and information directed at solving multiple scale and multiple process questions in the hydrologic sciences. The intent is to provide hydrologic observations that will supplement hypothesis-driven experiments conducted by hydrologists outside of the HOs. These observations should be sufficient to:

- Construct current time series and spatial patterns of important hydrologic variables at multiple scales, such as precipitation amount and intensity, energy fluxes, and ET, discharge, snowpack properties, soil moisture, water-table elevation, hydraulic gradient, channel morphology, solute and isotopic content, and sediment content.
- Extend the time series backward in time using a combination of historical data and paleo proxies.
- Characterize current and past land use/land cover/land management.
- Quantify the demand side of the basin water balance.
- Provide the support infrastructure to field test new instruments.

The optimal configuration of each HO will evolve with experience. As of now, we believe that the best model for an HO is a central administration at an academic institution with one or more distributed field stations, and strong partnerships with agencies that maintain smaller research sites within the HO. The central site would house personnel, analytical facilities such as soil and water quality laboratories, laboratory space to process field samples and to benchmark instruments, and the computer environment for data processing. The type, number, and size of field stations would be determined for each individual HO.

Instrumentation and measurements will be spatially distributed according to two criteria: (1) provide information on variables that will be systematically measured throughout the HO, such as rainfall rate and distribution and (2) support a higher density of sampling at nested basins that will represent three sections of the HO: upland, upland-valley transition, and valley locations. This nested scheme borrows from the WEBB report and USGS review (see www.usgs.gov/webb). At least one of these nested basins could be urban.

Permanent installations will be established along the main stem of the river basin. We anticipate a minimum of four sets of stations, at approximate scales of 1 km^2, 10 km^2, 100 km^2, and 1,000 km^2 in order to directly assess scaling properties and evolution of stream channel flow quantity and quality. The number of stations at each scale will need to be determined based on expected or observed heterogeneity of driving watershed conditions. In addition to gauging stations nested through the stream network, sampling of other key stores and fluxes within the watershed by multiple, robust instrument deployment will be allocated based on observed or expected system heterogeneity and available resources. Emphasis will be placed on characterizing basic hydrologic component stores, residence time, and boundary conditions. For example, stable and radiogenic water isotopes and solutes collected at multiple scales from different reservoirs (precipitation, groundwater, stream flow) will provide hydrologists with the information to evaluate how hydrologic flowpaths and source waters change temporally and spatially. It is expected that instrumentation and sampling over an HO will include:

- Meteorological variables sufficient to close the energy and water balances, including solar and net radiation; wind speed; air temperature and relative humidity at one height; precipitation amount and intensity; soil temperature and moisture; and heat flux. The Oklahoma mesonet offers some lessons on both network design and station design.
- Precipitation chemistry will be measured weekly following the protocols of the National Atmospheric Deposition Program.

- Discharge will be measured continuously in reaches that extend from the headwaters to the mouth of the river basin.
- Geochemical and other water-quality variables will be measured weekly at each gauging station, including major solutes, organic matter, sediment, water isotopes, and isotopes of some additional constituents such as ^{13}C of dissolved organic matter.
- Subsurface hydrologic measurements including soil moisture, water flux through zero-tension soil lysimeters, and water-table height will be required and accomplished in coordination with the streamflow and meteorological stations.
- Geochemical and water-quality variables in each of the subsurface reservoirs will be measured weekly.

In addition to the above suite of standard measurements along the main stem of the river traversing the HO, more intensive measurements will be conducted at the nested test basins, including:

- Meteorological variables at a higher density, emphasizing such variables as precipitation quantity and intensity. An eddy flux station will be collocated with a meteorological station in each test basin to make accurate measurements of land-atmosphere energy and water exchanges at a point. Denser measurements at the smaller-scale plots (<50 m^2) are needed for issues such as partitioning rainfall and snowmelt into runoff versus infiltration.
- Subsurface measurements using geophysical tools and observation wells with distributed coverage for systematic analysis of the spatial distribution of variables.
- Concurrent with physical observations, water-quality sampling of surface, soil, and ground waters will be measured for such variables as dissolved organic carbon (DOC) and chlorophyll *a*.
- Land cover and land use on seasonal and annual bases, using a combination of remote sensing and ground surveys.

Borrowing from the WEBB report and USGS reports, small basins will be heavily instrumented at highland, mountain-valley transition, and valley locations. Cooperative ventures with federal water agencies will be a key component to fund instrumentation and data collection. Basic instrumentation at these sites may include:

- Soil-moisture probes
- Nested, multi-level piezometers
- Tensiometers
- Infiltrometers
- Interception gauges and sap-flow meters
- Similar instruments as along the main stem

Deployment of more expensive instrumentation and technology is anticipated at these sites, particularly during intensive field campaigns.

Spatially distributed data become more important as basin scale increases. For example, the accuracy of precipitation input and ET output calculations at the basin scale are a function of the number and location of field measurements. We propose a two-pronged strategy: remote-sensing measurements with distributed climate stations. Remote-sensing measurements would include instruments such as radar, LIDAR, surface microwave, the suite of instruments on the EOS platform, and airborne hyperspectral systems.

Again, note that these measurements can be accomplished using off-the-shelf technology that is field-proven and relatively inexpensive.

CHARACTERISTIC SPATIAL DATA

Each HO will develop characteristic spatial data for the river basin, including:

- High-resolution DEM
- Topography
- Soils
- Geology
- Vegetation
- Land use

Some of these data sets may be standardly available in a set of locations. However, many may not be uniformly defined and agreed upon, and some may lack sufficient available (or existing) monitoring technology. An important task for the hydrologic observatory network, in conjunction with other working groups (e.g., Measurement Technology, Information Management) will be consensus on definitions, approaches, sampling and analysis methodology, and design and development of new measurement technology.

An HO should also recover, archive, and make available through the CUAHSI data system historical information on, for example, land use, hydrochemical attributes, precipitation, and snowpack.

A data manager at each HO will handle data entry, quality assurance, quality control, and metadata. The data manager will ensure the continuity and quality of the data stream to the CUAHSI Hydrologic Information Systems archive.

START-UP PLAN

- A hypothetical observatory prototype will be designed and budgeted through an interdisciplinary scientific workshop (as soon as possible).
- Preproposal RFP Issued (September 2003 – Due January 2004); each proposal must be a multi-university effort
- Successful preproposals are given six-month planning grants (April 2004)
- Full proposals due based on prototype design (October 2004).
- Selection of proposals by an independent committee (February 2005, NSF panel)
- Implement first set of observatories (June 2005)
- Data online (2006)
- Eventual build-out of the network

Lack of experience within the community in operation of these facilities at the envisioned nested spatial and temporal scales, with the coordination of observations and experimental measurement between disciplines, and the lack of baseline information for many candidate watersheds suggests one-year planning grants. While this information may exist for a set of watersheds at the envisioned scales, the pre-proposal 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.

When considering questions focused on water stores and fluxes, coupled with energy, sediment, nutrient balance, and transport at multiple scales, it is important to first determine the sampling density required to address significant, multiple scale heterogeneity in climate, soils, land use, geomorphology, and aquifer conditions. Taking the example of surface water gauging, if we postulate a 10^4 km^2 watershed with an average area threshold to support a 1st order channel of 1 km^2, a reasonable set of stream numbers (1st through 6th order streams) can be 5000, 1250, 300, 80, 20, 5, 1 (assumes a bifurcation ratio around 4). How many 1st, 2nd, 3rd, … order streams need to be gauged and with what spatial sampling scheme? How many require continuous long-term gauges, and how many can be gauged for shorter periods or by periodic sampling? Similar questions would need to be answered for groundwater monitoring wells. 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. We suggest on the order of 10 grants @ 50-100K for this portion of the HO network development.

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

ILLUSTRATED EXAMPLES

In this section we present examples of watersheds on the order of 10,000 km^2 with critical science and policy questions that currently lack the science base to achieve adequate solutions. The two sites are drawn from very different hydroclimatic regimes with significant differences in land cover, population, and geology. These sites are chosen to illustrate the potential scope of HO watersheds in terms of size, scientific questions, available data resources, and envisioned or developing larger scale instrumentation. *Their use here does not denote endorsement of these sites as candidates for Hydrologic Observatories.* Rather, they are used as convenient examples in two distinctly different climates and physiographic regions, and are expected to be two of many sites that may be proposed.

NEUSE RIVER BASIN, NORTH CAROLINA

Major Societal and Scientific Questions, and Available Hydrologic Infrastructure

The Neuse River Basin encompasses approximately 20,000 km^2 draining from the piedmont of central North Carolina through the coastal plain and into the Pamlico-Albemarle Sound. The basin includes the large, and rapidly expanding urban area of the Research Triangle (Raleigh, Durham, Chapel Hill), and large areas of agricultural and forest land. The lower watershed contains very large industrial livestock production—largely hog, but including significant poultry operations. Significant agricultural abandonment over the last century was accompanied by large-scale afforestation, which has now been reversed with expanding urban and reintensified agricultural sectors. Groundwater resources are varied, with the upper portion of the Neuse in the piedmont, underlain by crystalline bedrock with locally thick saprolite, while the coastal plain is underlain by relatively shallow sedimentary aquifers, but with a complex stratigraphy from the transgressing shoreline. Shallow groundwater resources in the coastal plain are subject to contamination and overuse, while water supply in the piedmont is from a mix of household and community wells, along with developed surface water supplies. Rapid urban growth has resulted in a heterogeneous mix of available water supply, with some rapidly developing communities around Raleigh chronically short of water and with frequent water-use restrictions, while other communities have planned adequate resources.

Major hydrologic concerns include export of nitrogen into the Neuse estuary and Pamlico Sound leading to eutrophication and fish kills; the adequacy of surface and groundwater supply given the mix of development, population growth, and recent drought; and hurricane-induced inland flooding. Eastern North Carolina has not yet recovered from flooding from Hurricane Floyd in 1999, which displaced entire communities, ruined thousands of homes, and killed more than 50 people.

Currently, there are almost 40 stream gauges operated by the USGS, many in partnership with local, state, and municipal agencies, with some record lengths in excess of 50 years. A detailed land use classification has been conducted by Lunetta et al (2001) at the EPA. This classification includes a network of ~1500 vegetation/surface cover plots, including ~400 riparian plots with GPS locations available on the web. As part of an effort to update floodplain maps in the aftermath of Hurricane Floyd, North Carolina has partnered with FEMA and NASA to produce a high-resolution, LIDAR-derived DEM for the full state.

From a water-quality perspective, urbanization and agricultural activity have greatly increased the introduction of fixed and reduced nitrogen in the Neuse watershed since the mid-1980s, yet water-quality data suggest that total nitrogen concentrations are virtually unchanged in the lower Neuse River and Estuary over the past fifteen years. What are the pathways and sinks for this nitrogen in the watershed? Is denitrification significant on a watershed scale and are there denitrification "hotspots" that need to be conserved? Is there potential for accumulation of nitrate in the deep groundwater? As a lagoonal waterbody at the base of the watershed, Pamlico Sound is perhaps the most important nursery area in the mid-Atlantic region. Despite this, the long-term impact of increased urbanization and agricultural activity on Pamlico Sound is poorly known, as it has been infrequently and sporadically monitored. Little hydrologic and water-quality data currently exist to assess the possibility of gradual eutrophication of Pamlico Sound or the impact of catastrophic events (hurricanes).

In summary, major questions include:

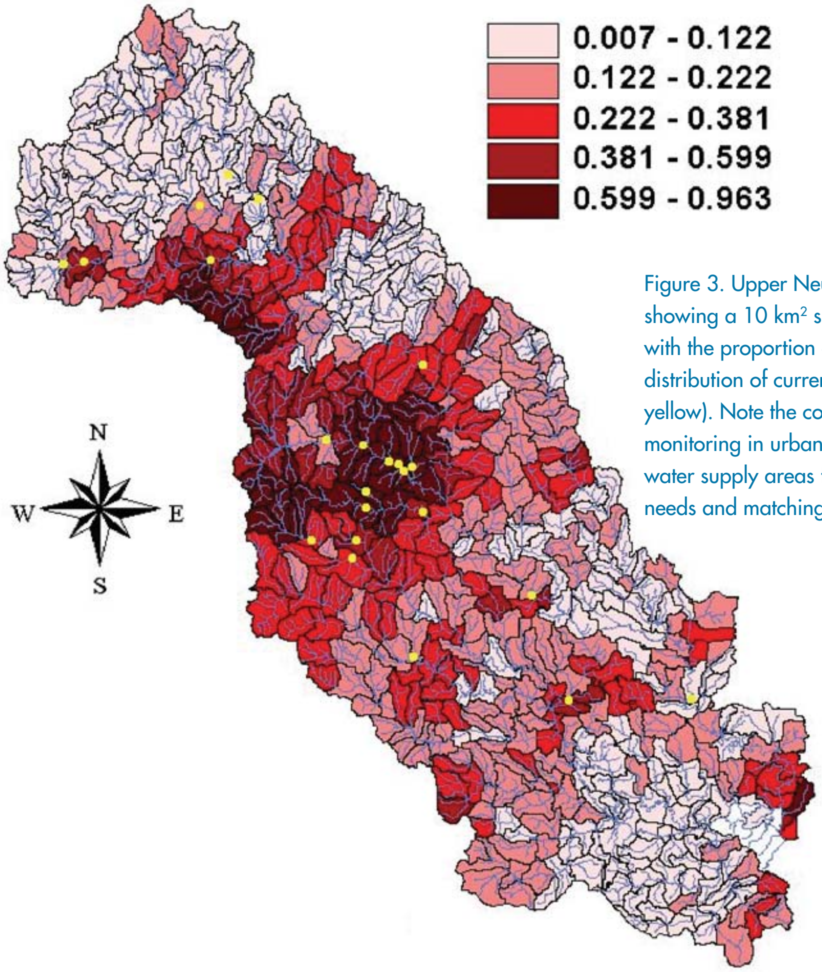
- What are the major sources of nitrogen export into the Neuse and how are these best controlled?
- What are the primary mechanisms of nitrogen retention in the watershed, and how are these linked to hydrologic processes?
- What is the relative impact of catastrophic events (e.g., hurricanes) in determining water quality and the status of

the aquatic ecosystem in the Neuse Estuary and in Pamlico Sound?
- Is long-term sustainability of the fisheries in Pamlico Sound compatible with urban and agricultural development of the Neuse watershed?
- What is the probability of additional catastrophic floods in the Neuse and adjacent coastal watersheds in the next few decades?
- Has development in the urban portions of the Upper Neuse exacerbated flood potential downstream and led to changes in the potential inundation area?
- Are surface and groundwater supplies sustainable given the mix of population growth, low- and medium-density urban sprawl, periodic drought, and potential ground and surface-water contamination from urban and agricultural sources?

The Upper Neuse drains approximately 7500 km^2, in the piedmont and coastal plain, containing Raleigh and the Research Triangle, one of the most rapidly urbanizing areas of the country. Figure 3 shows the existing set of USGS stream gauges are dominated by more urban locations, areas around public water supplies, and mainstream sites following cooperative funding by state and local municipalities. While these gauges provide long-term records, greater representation of agricultural and forest sites would be important to investigate the heterogeneity and dynamics of runoff and nutrient delivery from the full watershed. This representation shows the Upper Neuse partitioned into subcatchments with a threshold of 10 km^2 and the proportion of urban land. Similar distributions at 1 km^2, 100 km^2, and 1000 km^2 summarizing land use/land cover statistics would be used to design a sampling strategy that would be capable of examining scaling of runoff, flood peaks, and nutrients.

The Neuse is part of the Albermarle-Pamlico NAWQA study area, so it is nested inside a larger, more sparsely monitored site with an emphasis on water quality. Recently, the USGS, EPA, State of North Carolina, and the regional universities conducted a series of coordinated investigations related to monitoring and modeling of Neuse River water quantity and quality, incorporating atmospheric sources and surface and groundwater interactions. The result of this recent collaborative Neuse modeling and monitoring study was the development of a TMDL (total maximum daily load) for nitrogen addressing violation of the chlorophyll standard in the Neuse Estuary. A central element of this TMDL is the need for post-implementation water-quality monitoring to assess compliance with the standard. At present, there is little understanding and experience in designing and carrying out this type of monitoring, particularly when analytically integrated with the water quality modeling to update and improve forecasts. A novel measurement campaign currently in operation is the use of real-time water-quality sensors at several sites in the Neuse (rivernet.ncsu.edu) that produce high temporal resolution for a set of water-quality parameters including nitrate, dissolved oxygen, turbidity, temperature, and pH, as well as stage.

The combination of monitoring and measurements currently taken by federal and state agencies as well as local universities forms the base for a comprehensive study of the links of hydrology to watershed biogeochemistry and societal interactions. However, the current set of activities including shorter- and longer-term individual and agency projects are not centrally coordinated, and funding is subject to considerable instability. Provision of centrally maintained research infrastructure, and development of a consistent interdisciplinary framework for the study of this basin, while promoting and taking advantage of the spontaneity and creativity of the scientific community would benefit and advance hydrologic science and the local communities and ecosystems.



Proportion of Urban Land
and Existing USGS Gauges
Upper Neuse

Figure 3. Upper Neuse River Basin showing a 10 km^2 subbasin threshold with the proportion of urban land and the distribution of current USGS gauges (in yellow). Note the concentration of stream monitoring in urban (Raleigh, Durham) and water supply areas following municipal needs and matching funds.

THE USDA-ARS WALNUT GULCH EXPERIMENTAL WATERSHED AND EXPANSION INTO THE SAN PEDRO BASIN

Relevant Science Questions and Hydrologic Infrastructure and Characterization to Address Them

This illustration of hydrologic infrastructure to address critical science questions is drawn on actual experience in expansion beyond the spatial scale of the USDA-ARS Walnut Gulch Experimental Watershed[1] (WGEW) in southeastern Arizona illustrated in the upper right-hand corner of Figure 4. The WGEW, in operation since the 1950s, is a densely instrumented 150 km^2 watershed with 28 nested subwatersheds ranging in scale from 0.002 to 112 km^2 , 85 recording rain gauges, two energy balance/carbon flux stations, eight sediment collection stations, a long-term remote-sensing archive, and on-site shop, lab, and visiting scientist facilities. In addition, the WGEW has been a base for numerous intensive experimental campaigns.

Relevant Science Questions

1. What are the scaling properties of runoff, infiltration, and ET across a broad range of spatial scales (hillslope to watershed to basin)?
2. What is spatial and temporal distribution of regional aquifer recharge over the basin?
3. What is the quantity and source of water used by riparian vegetation and the nature of surface-groundwater-vegetation interactions from event to decadal periods?
4. What is the nature of coupling between the carbon and nitrogen cycles in semi-arid riparian systems and how do these cycles couple with the hydrologic cycle to determine population dynamics of native and exotic riparian plant species?
5. How do documented large area changes in land cover impact and affect the hydrologic cycle?

The expansion beyond the scale of the WGEW was motivated not only by the science questions above, but also by the needs of the Upper San Pedro Partnership (USPP). This is a consortium of 20 NGOs, local, state, and federal agencies whose goal is assuring an adequate long-term groundwater supply is available to meet the reasonable needs of both area residents (current and future) and the first congressionally designated San Pedro Riparian National Conservation Area (SPRNCA). Much of the hydrologic infrastructure and monitoring work in the larger San Pedro discussed below is being coordinated through the USPP. This additional infrastructure is essential to address the USPP goal, and to achieve this goal the science questions outlined above must be answered.

While a wealth of knowledge concerning semi-arid hydrologic processes has been (dating from the 1950s), and continues to be, developed using observations from the WGEW (see http://eisnr.tucson.ars.ag.gov/Publications/Search.html) the above science questions cannot be fully addressed using the WGEW due to several limitations in its size and observational structure. This was partly by design as many of the ARS Experimental Watersheds were selected to isolate a particular dominant hydrologic process or the effects of particular agricultural practices. For example, the Reynolds Creek ARS watershed in Idaho was selected largely because its hydrologic response is dominated by cold climate and snow processes and the Little River Watershed in Georgia was selected because its hydrology is dominated by groundwater dynamics in the coastal plain. The WGEW was selected to focus study on surface water dominated hydrologic response from summer rainfall. To isolate surface

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[1] Additional details on the nature of the hydrologic infrastructure of the 150 km^2 WGEW can be found at http://www.tucson.ars.ag.gov/unit/Watersheds/WGEW.htm.

water processes, the WGEW was sited so that the depth to the regional groundwater aquifer is from roughly 40 to 50 m. Because of this, a robust semi-arid riparian system is not sustained within the WGEW; this precludes the study of science questions three and four above. Likewise the scaling question (#1) cannot be fully explored using the WGEW. This is illustrated in lower right-corner of Figure 4, which plots mean annual runoff versus drainage area for four ARS Experimental Watersheds in different regions of the country One cannot extrapolate these relationships to the larger basin scale envisioned in an LTHO. Note the radical change in scale behavior if the three USGS gauging stations along the main stem of the San Pedro are added to this figure (in blue). This change occurs because at the larger San Pedro scale

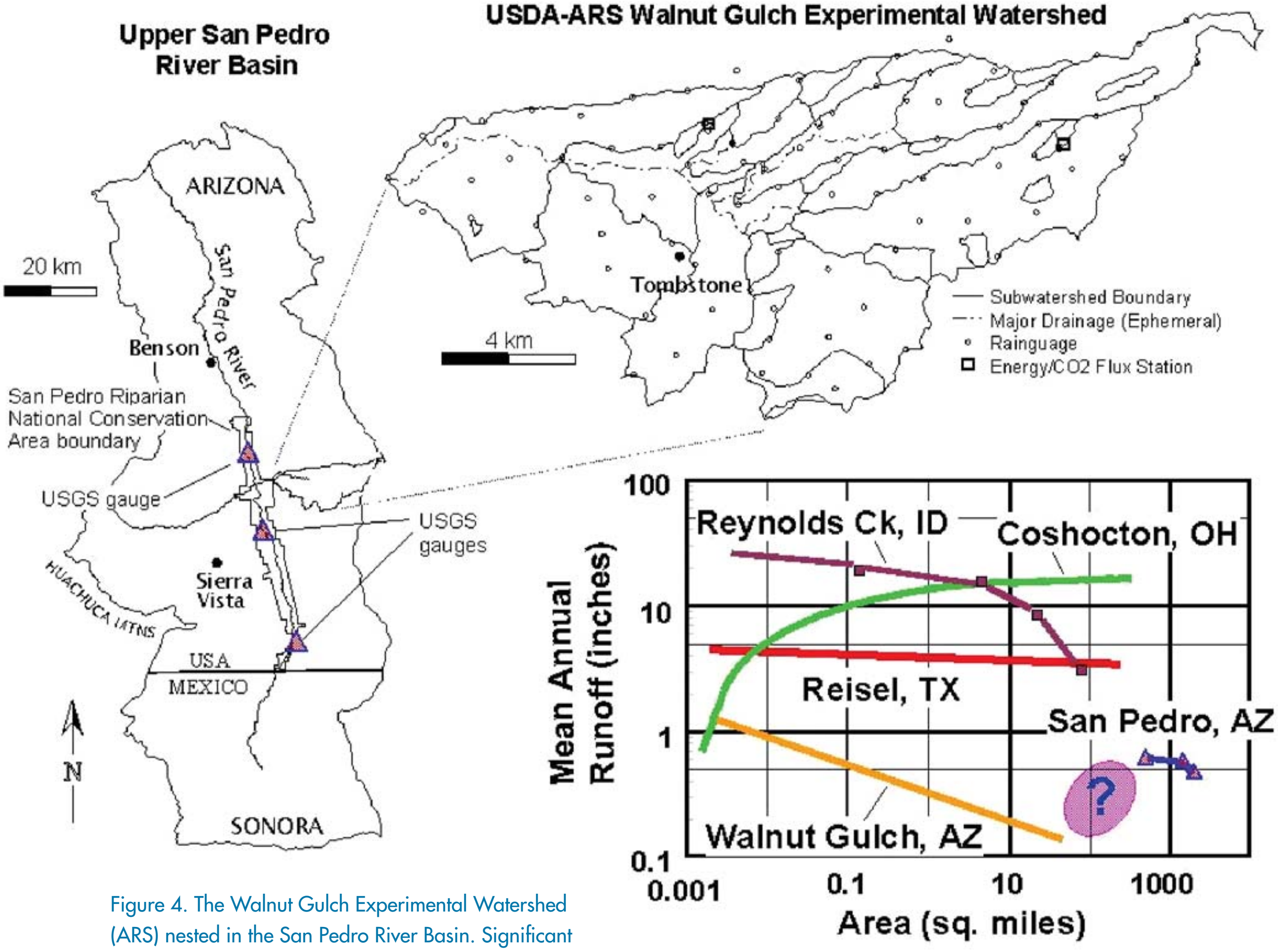

Figure 4. The Walnut Gulch Experimental Watershed (ARS) nested in the San Pedro River Basin. Significant thresholds in runoff and streamflow reflect scale dependence of surface/groundwater interactions.

(>7000 km^2) groundwater influxes to the San Pedro River[2] become important. To meet the goal of the USPP it is essential to address the science question on recharge (#2) and riparian water use (#3).

To address the science questions above, a variety of experimental campaigns and hydrologic infrastructure and basin characterization efforts have been or are being implemented in the San Pedro beyond those in the WGEW. This effort was initiated by the Semi-Arid Land-Surface-Atmosphere (SALSA) Program starting in 1995. The SALSA program conducted several intensive, multi-season, experimental campaigns with focus areas changing from the US to Mexico across several years. Experimental design and research results are summarized in the *Journal of Agricultural and Forest Meteorology* SALSA Special Issue (Nov. 2000, pp. 1-323), which can also be viewed at: http://www.tucson.ars.ag.gov/salsa/research/research_1999/jafm/paperindex.html.

Building on the SALSA efforts, the following infrastructure and basin characterization is being conducted by the USGS, ARS, EPA, US Army, University of Arizona, and Arizona State University, and the SAHRA NSF Science and Technology Center (http://www.sahra.arizona.edu/) to address the stated science questions.

Infrastructure and Sampling Frequency[3]

- Establish met, soil moisture, and energy and CO_2 flux stations in desert brush, desert grass, riparian zone, and ponderosa pine (mountain location) (20-minute interval).
- Increase USGS stream gauge density from 4 to 11 stations (see http://water.usgs.gov/az/nwis/current/?type=flow, San Pedro River Basin) (15-minute interval).
- Establish 17 cross sections over perennial, intermittent, and ephemeral reaches in 60 km riparian reach with ~3 shallow recording piezometers and stage recorder at each cross section (20-minute interval) with detailed vegetation characterization (pre- and post-monsoon).
- Establish micro-gravity network of observation stations to detect changes in aquifer storage (quarterly).
- Install ~90 temperature sensors in ephemeral channels to detect the onset and duration of surface flow (30-minute interval).
- Instrument ~30 deep monitoring wells in regional aquifer (10 in riparian corridor) (hourly interval).
- Determine stream, shallow well, and soil nutrient status at selected locations (~quarterly).
- Analyze selected regional aquifer, vadose zone, rainfall, and plant water stable isotope (seasonal).
- Sample biomass at selected locations coordinated with imagery acquisition (2 to 4 times/year).
- Install three dry fall gauges for atmospheric deposition (~monthly).

Basin Characterization[3]

- Paleoclimatic characterization using tree-ring analysis
- Retrospective land cover classification and change analysis from satellite imagery from the 1970s, 1980s, and 1990s.
- TERRA/EOS land validation area enabling acquisition of frequent and varied remotely sensed dat.a
- Aerial EM (electro-magnetic) surveys for basin subsurface characterization.
- Aerial photography and detailed classification of riparian vegetation (1997, 2000, 2004, 2008).
- Acquisition of IFSAR over a large portion of basin for detailed topographic data.

[3] This hydrologic research infrastructure and basin characterization has been implemented largely through efforts supported by the USPP with significant leveraging from Federal hydrologic science agencies (e.g., ARS, USGS, EPA, NSF though the SAHRA STC, US Army) and a variety of projects funded through a number of universities.

[2] Additional background information on the San Pedro River can be found at: http://www.tucson.ars.ag.gov/salsa/archive/documents/plans/science_plan_current.html, and in Goodrich et al., 2000. Preface paper to the Semi-Arid Land-Surface-Atmosphere (SALSA) Program Special Issue. *Journal of Agricultural and Forest Meteorology* 105(1-3):3-20.

- Approximately 20, 20-meter boreholes with vertical characterization of physical properties, and chloride, tritium, and silicon(32) profiles.
- Compile, document, and make most GIS data layers available (see http://www.epa.gov/esd/land-sci/html2/sanpedro_home.html).
- Detailed geophysical surveys in riparian alluvial aquifer.

Of course, the nature and character of the hydrologic infrastructure and basin characterization will depend on the nature of the science questions being addressed and the hydroclimatic and land use characteristics of the basin. In addition, it should be noted that entire predetermination of instrumentation types and locations was not possible. Through iterative acquisition of knowledge the hydrologic infrastructure has been developed incrementally. While many investigators are studying various facets of hydrological science to address the questions noted above, few if any to our knowledge are investigating all these facets simultaneously within a single large basin. Herein lies the true power of an LTHO to quantify the nature and degree of coupling and interdependence between hydrologic, climatic, and ecological process with policy and resource management.

BUDGET ESTIMATES

The start-up and annual recurring costs of an HO are estimated here on the basis of analogy and extrapolation from existing watershed facilities, and the envisioned requirements for operation. Each site will have a varying level of infrastructure and data resources available at the outset, with an equally varying level of support from collaborating agencies. The federal hydrologic agencies, including the USGS, ARS, and FS, are expected to provide long-term, stable collaboration with CUAHSI for some sites. Other than sites in which these agencies have substantial investment and infrastructure in place (e.g., existing ARS, LTER sites, USGS gauges), or long-term commitments to develop new sites, the CUAHSI budget should be capable of supporting all core, long-term monitoring and measurement activity, as well as information management and dissemination. Additional funding or in-kind contributions from other collaborating agencies (e.g., state, county, NGO) will provide strong leverage in extending or intensifying the HO activity in specific areas of interest to these partners. Lead universities on the HO proposals will also be expected to provide a level of matching funds with in-kind contributions of items such as faculty release time, office space, laboratory space, and graduate student support.

Based on experience in start-up and operation of LTER and ARS sites, the Oklahoma mesonet and USGS facilities, we can outline expected time tables and expenditures for the HOs. Expenses should be partitioned into start-up costs, including capital equipment, construction of facilities, and personnel; and annual operations, including equipment maintenance and replacement, administration, technical and education/outreach personnel, field supplies, and travel. A third category of expenses will be associated with shorter term field campaigns, which will operate to more intensively characterize diurnal to seasonal patterns of integrated hydrologic processes as directed by driving science questions.

First, we expect that the HOs will require a start-up time of 3 to 5 years before a functioning, interdisciplinary sampling and synthesis framework is fully established. Start-up costs will be distributed over this defined period. It is counterproductive to attempt to develop and implement all aspects within one to two years as the development of the system will be a learning process (at least for the first HO) and will require careful and time consuming coordination between a set of individuals and institutions. Those sites that are further along in this regard at the outset will take a shorter time and this will be a consideration in site selection. The preproposal planning grants are partially designed with this in mind.

After the start-up period, the HOs will continue to evolve and develop their observational and measurement capability in response to advances in measurement technology and evolving scientific and water management issues. This will be funded from a set of sources including periodic upgrade funding from CUAHSI (analogous to LTER headquarters periodic disbursements to upgrade equipment); field campaigns which will implement new experimental or monitoring infrastructure, some of which will be designed to remain with the HO; and contributions from research partners or independent scientific teams concerned with specific scientific or management issues.

Start-up costs will include capital for collection of

1. Baseline watershed characterization of the watershed, including high-resolution topography, land cover, soils, hydrogeologic conditions, and socioeconomic patterns and activity. Some of these will require periodic remeasurement.
2. Installation of more standard monitoring networks of stream gauges, meteorological stations, groundwater observation wells, all with digital wireless communications,
3. Installation of more specialized equipment that may be unique to the specific HO.

The emphasis on developing scaling theories as part of the CUAHSI mission suggests sampling is done over four orders of magnitude. This requires substantial investment in monitoring infrastructure within the nested watershed system. Based on experience in LTER and ARS sites, the number of installations envisioned and approximate unit costs of installation, a start-up cost of $20,000,000 disbursed over 3 to 5 years per site is estimated.

For core, recurring operations the following personnel budget items are required:

1. Hydrologic Observatory Director: Potentially a university faculty member with substantial release time, cost-shared with university.
2. Associate director for day-to-day operation and coordination of the facility.
3. Education and outreach coordinators and an information manager.
4. 12-15 technical service employees for field sampling, instrument service, information management (QA/QC, database, dissemination), and lab analysis.

Depending on the site, activity may be concentrated in specific seasons or locations. As an example, the San Pedro and Walnut Gulch site have more concentrated sampling during the three month monsoon season, with personnel available for other activity during the dry period. In the Neuse, there is not a distinct wet season, and sampling is typically continuous through the year. This produces different efficiencies and cost savings in budget, or the ability to reallocate funding to other, novel science questions.

Based on previous experience at these and other sites, an expected $2-3M/year will be required for annual operating expenses.

SUMMARY

It has been widely recognized in the scientific and policy community that major advances in hydrology and water resources will require the development of significant interdisciplinary theory and measurements to integrate the roles of atmospheric, ecosystem, and societal interactions, as well as the information necessary to pose and test scaling relations. At present, our ability to provide the framework necessary to accomplish these goals is limited by fragmentation between water-related disciplines in locations of research study sites, time scales of data collection and information generation, and by a lack of coordination in sampling, analysis, and synthesis of key hydrologic cycle components. While a set of water and water-related monitoring programs currently exist that would support elements of our proposal, none are currently sufficient to meet the challenges posed by the community's major scientific questions. The HOs are proposed to integrate and leverage elements of these programs, and build the additional components required to create the research infrastructure necessary to achieve significant advances in hydrologic science in the coming decades. It is emphasized that the focus of HO proposals must be to design, develop, and operate community research infrastructure to aid in realizing CUAHSI scientific goals. It is not a mechanism to propose the type of research that heretofore has been submitted to the NSF Hydrology Program. As noted above, this type of research may be conducted within one or more of the HOs and will be evaluated under an independent review process.

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TECHNICAL REPORT #4