CUAHSI, a consortium of American universities with research programs in hydrologic science, has completed a prototype design for a network of hydrologic observatories (HOs), which are conceived to be instrumented river basins with areas of approximately 10,000 km$^2$. HOs can revolutionize hydrologic science by providing coherent, integrated, multi-scale data on physical, chemical, and biological phenomena that will address major environmental challenges such as eutrophication from non-point source pollutants, and long-standing hydrologic science questions such as actual evapotranspiration rates in complex terrains. This study has produced a management design that will lead from local science questions, yet also be responsive to network requirements. Criteria for evaluating proposed hydrologic observatories were also developed.

INTRODUCTION

The development of large-scale environmental observatories to advance scientific inquiry into a broad range of problems from climate change effects to eutrophication to loss of biodiversity has been the subject of debate in the United States during the past 5 years. The larger scale of these field facilities will revolutionize the science in two important ways:

- *direct study of intrinsically large-scale phenomena* such as exchange of groundwater and surface water at the river-basin scale
- *easier testing of transferability of concepts* developed from small-scale studies by providing a broader range of well characterized locations

Hydrologic scientists bring a unique perspective to this problem by applying the hydrologic cycle as an organizing principle to landscape-scale studies. Applying the concepts of conservation of mass and energy budgets allows for quantitative tests of our
understanding at these large scales. From this perspective, the catchment emerges as a natural unit of the landscape, with boundary conditions that are convenient for hypothesis testing and model development. Because water serves as a solvent, as a transport vector, and as a critical factor in determining species distribution, the catchment is a meaningful landscape unit for a broad range of disciplines beyond physical hydrology including geomorphology, biogeochemistry, and ecology.

**SCIENCE VISION**

Through a series of community workshops, CUAHSI has identified an integrated set of infrastructure elements, called HydroView, to support hydrologic observatories as well as the community at large, consisting of an informatics, instrumentation, and a synthesis facility (Figure 1).

![Figure 1. Elements of HydroView](image)

The goal of HydroView is to dramatically advance society’s ability to estimate the terrestrial distribution of water and associated biogeochemical elements at any scale. This step forward requires innovative scientific concepts, measurements, and models. HydroView will take this step by implementing an unprecedented observing strategy focused on critical environments. The focus on observations arises from the recognition that hydrologic science has many concepts and models of these concepts that have not yet been rigorously tested. The integrated, multi-scale data to be collected at hydrologic observatories will provide the more powerful test required to advance the science.

Through a series of community workshops, CUAHSI has identified improving the predictive understanding of the following five science topics as the top priority:

1. Linking hydrologic and biogeochemical cycles
2. Sustainability of water resources
3. Hydrologic and ecosystem interactions
4. Hydrologic extremes, and
5. Fate and transport of chemical and biological contaminants

Each of these topics can be addressed by three cross-cutting themes:

1. Forcing, feedbacks, and coupling
2. Scaling, and
3. Prediction and limits to predictability.

The integrated data collected hydrologic observatories will address all of these topics in a cost-effective manner because of the degree of overlap in the data required. Consider, for example, the measurement of evapotranspiration. Currently, an ecologist measures water flow in the xylem of a tree in one place, a hydrologist measures soil moisture and energy fluxes in another place, and an atmospheric scientist uses an eddy covariance tower to estimate evapotranspiration in a third place. By bringing these measurements together in one place, each can still pursue his or her science question, but the power to test which factors control evapotranspiration is vastly increased by the redundancy of the measurements. Furthermore, measurement of carbon dioxide concentrations on the eddy covariance tower can be added at a small incremental cost, but the ecologist or carbon modeler also has all the hydrologic data at her disposal to place those carbon fluxes into a larger context. This is the power of integrated data.

DESIGN CONCEPTS

Core Data

A significant challenge in the design of hydrologic observatories is the designation of “core data,” defined as data that provide a characterization of the catchment that is useful for a broad range of questions. However, any characterization that is truly hypothesis independent could easily consist of tens of thousands of physical, chemical, and biological measurements that are measured continuously in time and space. Because this is clearly infeasible with limited resources, any feasible characterization will necessarily be dependent upon the hypotheses considered. Of course there is a spectrum of dependence. If one considers a three-dimensional space whose axes are spatial coverage of data, temporal frequency of sampling, and resolution of the data, where the orientation of the axes has the most complete coverage, highest frequency and highest resolution at the origin, then data near the origin are less hypothesis dependent and data farther from the origin are more hypothesis dependent (Figure 2a).

For example, radar reflectance, which can be interpreted as precipitation rates, have complete spatial coverage and a high sampling frequency, placing them near the origin in the x-y plane, but may have a coarse spatial resolution, placing it somewhat up the z-axis. LIDAR measurements of topography are high resolution and have complete spatial coverage, but are measured only infrequently; while, soil moisture measurements made by a tensiometer may have high resolution and high temporal frequency, but a very
limited spatial extent. Viewed in this manner, the challenge in the design of a hydrologic observatory is determining the boundary between the core data and the investigator data (Figure 2b).

Figure 2. (a) Spectrum of hypothesis dependence. (b) Boundary between core data and investigator data.

Many multidisciplinary environmental networks have foundered on the definition of core data. A simple concatenation of each scientist’s wish list for data rapidly becomes infeasible. On the other hand, how is the utility of any feasible data set for advancing the science determined?

In the prototype study, we recognized that virtually all hypotheses that we considered required the characterization of four basic properties of the catchment, where each property refers not only to water, but also to sediment, nutrients and contaminants:

1. Mass in each “store”
2. Residence time within stores
3. Fluxes between stores
4. Flowpaths among the stores

In all cases, “stores” refers not only to surface and subsurface areas of the catchment, but also the atmosphere. In our discussions of the Neuse basin, we considered the control volume to be the entire catchment area in the horizontal dimensions and extending 1 km below land surface to 15 km above land surface in the vertical.

Therefore, our proposed definition of “core data” is those data that contribute to the quantitative estimation of these properties at a range of spatial scales. Particularly at large scales, these properties cannot be directly measured and must be inferred. We recognize that, in many cases, estimating these properties is a challenging research topic in its own right.
Hydrologic observatories as community resources

To justify the level of investment a hydrologic observatory will require (our base scenario was an annual operating budget of US$3M and a capital budget of US$10M), these facilities must serve as community resources attracting a large number of scientists across a range of disciplines. To ensure that, the following design principles were adopted:

1. **A professional staff**, headed by a PhD-level scientist, will operate the hydrologic observatory. This staff is accountable to the community through a CUAHSI governing body.
2. **Core data** will be immediately available to everyone using a common data model across all hydrologic observatories. The primary duties of the observatory staff will be to collect the core data and to populate the common data model.
3. **Site access** will be on an equal basis for all scientists, subject only to coordination constraints among existing projects. The observatory staff will provide site coordination, secure necessary permits, and enforce any permit restrictions.
4. **Local support** will be provided to make the site attractive to remote investigators including laboratory facilities, field vehicles and other logistical support. Professional staff will assist in collection of investigator data where resources permit.

Size and scope of hydrologic observatories

Hydrologic observatories must be of a sufficient size to permit the examination of all interfaces in the hydrologic cycle, including the land-surface and atmospheric interface. The minimum size for studying mesoscale atmospheric processes is on the order of 10,000 km$^2$, roughly 2 orders of magnitude larger than typical instrumented basins. This design size is not meant to be a rigid constraint. In some settings, particularly in the arid West of the United States, significantly larger basins must be considered. In other settings, such as the West Coast, smaller parallel basins must be used. In other settings, topographic divides have little hydrologic meaning and effective basins must be defined by groundwater divides. In all cases, the critical factor is the choice of boundaries that enable estimation of the four fundamental properties listed above in the most efficient and most precise manner.

A national network of hydrologic observatories is also envisioned. This will require a coordination of effort to ensure comparability of data. A common data model, common protocols, and meta-data standards will be required for this effort to succeed. These tasks will require substantial investment and coordination with government science agencies, such as the U.S. Geological Survey, U.S. Forest Service, the Agricultural Research Service, and National Resource Conservation Service. The prospect is daunting, but advances in informatics and technology services make this feasible. The CUAHSI Hydrologic Information Systems group is currently at work on the data model and anticipates that a prototype will be available well in advance of the establishment of the first hydrologic observatory.
Although our current focus is on the United States, the data model and all data protocols will be made available to all interested parties through our web site. We seek to coordinate our efforts with studies in other nations and to work closely with groups such as the International Association of Hydrologic Science’s Prediction in Ungaged Basins (PUB) initiative.

Observatory Design Team
Given the design concepts and broad science topics described above, an observatory design team’s role is to pick a set of hypotheses of interest to them and to define a data set that will test those hypotheses. If our contention is correct, these hypotheses will require the estimation of the four fundamental catchment properties described above. The observatory design team must articulate how to delineate the basin into stores (for example, the number of vertical layers, horizontal compartments, etc.), designate which data are required to estimate these properties, and propose an analytical approach to convert the data into estimates of these properties. These data become the core data, which are the community product. Presumably, these data alone will not be sufficient to test the hypotheses and additional data will be collected. These additional data are “first publication” data that the investigator retains the right to publish, although they will be released to the public after a specified period.

In this manner, the observatory design team performs a community service (by defining the core data), and receives an incentive for that service (the ability to advance their own science with first-publication rights to critical data). In this way, we are also assured that the data are sufficient to answer some science questions. The core data, it must be stressed, are made immediately available to all scientists.

The observatory design team develops a specific work plan for the collection of the core data. This work plan is subject to review by a CUAHSI governing body to ensure compliance with network data standards and completeness. CUAHSI may add additional parameters to enhance data comparability across observatories, but the observatory design team will be assured of getting the data necessary for their hypotheses. The approved work plan is then given to the Observatory Staff to execute. The observatory design team does not control the collection or access to the core data. Periodic meetings between the Observatory Staff and the design team will be necessary to assess progress.

EVALUATION CRITERIA

Because the design approach allows for local variation and encourages creativity on the part of the observatory design team, criteria for evaluating proposals for hydrologic observatories are needed. We have developed the following criteria:

1. **Hypotheses posed.** Do the design hypotheses address at least 3 of the 5 priority topic areas? Are the cross-cutting themes addressed? Are the hypotheses interdisciplinary? Are they innovative and exciting?
2. **Design.** Does the design provide estimates of the fundamental catchment properties across a range of spatial scales, including the entire basin (or basins)? How are intensively instrumented sub-basins combined with more extensive, survey or synoptic data? What proportion of the data funded by this effort will be designated as “core data”? Is the design justified through quantitative analysis? Are benchmarks specified to gage increase in understanding through this effort? Is there the adaptive use of models to guide field data collection?

3. **Existing data.** How are existing data (including those collected at research sites and monitoring data collected by government agencies) leveraged in the design? Is full advantage taken of them?

4. **Institutional support.** Is there evidence of active support by government agencies and non-governmental organizations in the hydrologic observatory? Do stakeholder groups, such as basin commissions, support the effort and will they assist with access to private lands and other permitting issues?

5. **Education and outreach opportunities.** Have these opportunities been identified and is there a credible plan for pursuing these opportunities?

Although CUAHSI will not make funding decisions (such decisions are reserved by the funding agencies), these criteria capture the key aspects which we believe are necessary for the successful operation of a hydrologic observatory.

**CONCLUSIONS**

At the outset of this prototyping effort, a more centralized approach was envisioned for the design of hydrologic observatories. However, the complexity and myriad peculiarities of individual basins render such an approach ineffective. Instead, we determined that design teams who are intimately familiar with the basin are needed to design the core data collection, but that this data must be cast in terms of transferable, fundamental properties of the catchment. The design challenge becomes one of balancing the interests of the observatory design team with the network requirements of comparable data.

As of this writing (April, 2004), a pilot network of 5 observatories are planned for funding. The first two observatories will begin operation in the fall of 2005, followed by a third in 2008, a fourth in 2009, and a fifth in 2010. This staggered implementation will allow operational experience to be gained and will help to ensure the success of hydrologic observatories in meeting the goals we have set for them.

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