ENHANCING WATER CYCLE MEASUREMENTS FOR FUTURE HYDROLOGIC RESEARCH

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A new, community-based effort aims to transform hydrologic science by supporting new techniques to measure hydrologic processes at a wide range of time and space scales as well by characterizing the linkages among those diverse scales.

Advancing scientific knowledge with measured data often constitutes a causality problem. In hydrologic research, the insight and knowledge derived from innumerable scientific efforts are informed by the availability of measurements, while gaps in measurements constrain scientific exploration. All too frequently, a common attribute of hallmark hydrologic research is its narrow focus within a subdiscipline (e.g., groundwater, hydrometeorology, surface water, etc.). Timely and emerging suites of technologies are necessary to couple the water cycle subdisciplines, and to advance science questions that are currently challenged due to limited resolution in spatial and temporal measurements. This paper describes a community initiative that identified suites of instrumentation, capable of enhancing future water cycle measurements at a resolution and extent (Javaux and Vanclooster 2006) not previously explored in detail, as well as a method to support and deliver these instruments to principle investigators (PIs).

Beginning in 2002, the Consortium of Universities for the Advancement of Hydrologic Sciences, Inc. (CUAHSI; information online at www.cuahsi.org/),

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established the Hydrologic Measurement Facility (HMF) to transform watershed-scale hydrologic research (broadly based on mission statement 1, sidebar 1), and to facilitate access to advanced instrumentation and expertise in support of these endeavors (based on mission statement 2, sidebar 1). This coordinated effort is organized around three general study areas: water cycle (WC) science, geophysics, and biogeochemistry. The preliminary task of the HMF coordinating group was to seek input from the hydrological science community to determine the needs that the HMF could meet and to develop innovative ways to provide this support without creating competition for PIs, and in fact, create new collaborative opportunities with new and existing research efforts. Here we present the consistent vision that emerged through the following three activities: i) integrating the community's directives from the CUAHSI's Science Advisory Team (SAT) and the research community, ii) defining new opportunities that can be created through enhanced measurements, and iii) identifying emergent water cycle instrumentation, which can foster broad scientific synergies.

COMMUNITY INPUT. The CUAHSI SAT identified three themes that broadly characterize the scientific challenges for predicting, detecting, and managing water in a changing environment (sidebar 2). The SAT advocates modifications to current methods to address emerging scientific challenges. Their strategy includes enhancement of existing long-term observatories, development of new observatories (e.g., Krajewski et al. 2006; Reed et al. 2006), and making observations in a campaign-style approach that would include event-based measurements as well as routinely planned activities. The SAT specifically recommends the acquisition of instruments to enhance our capability to make distributed measurements in space and time that are currently beyond existing infrastructures, to develop multidisciplinary observations through complementary instrumentation that can be deployed simultaneously at comparable scales, and to transition from *preconceived* deployment strategies toward responsive and adaptive real-time sampling strategies.

The CUAHSI HMF's 2005 survey (Robinson et al. 2006; cf. www.cuahsi.org) elicited the hydrological sciences community's perspective on its measurement, instrumentation, and support needs and assessed the level of support for community instruments. Of the 23 topics, there was overwhelming support for the following four major initiatives:

1) improving the integration between measurement and modeling methodologies (80.6%),
2) improving the spatial resolution of measurements (79.7%),
3) enhancing our ability to take more and better measurements through distributed sensor networks (77.3%), and
4) improving our ability to measure and quantify the subsurface for hydrology (76.4%).

Respondents identified field-deployable instrumentation that could augment ongoing studies as a priority. The most commonly recommended instrumentation were atmospheric profiles [e.g., water vapor lidar, sodar radio acoustic sounding system (RASS)], geophysical equipment [including ground-penetrating radar (GPR) and electromagnetic induction (EMI) sensors], water quality sensors, weather radar, soil moisture sensing capabilities, and atmospheric flux towers. Importantly, respondents also pointed out that for success to occur, the required equipment

CUAHSI MISSION STATEMENT

CUAHSI's mission is to foster advancements in the hydrologic sciences, in the broadest sense, by

1) developing, prioritizing, and disseminating a broad-based research and education agenda for the hydrologic sciences derived from a continuous process that engages both research and applications professionals;
2) identifying the resources needed to advance this agenda and facilitating the acquisition of these resources for use by the hydrologic sciences community; and
3) enhancing the visibility, appreciation, understanding, and utility of hydrologic science through programs of education, outreach, and technology transfer.

SCIENCE CHALLENGES

Hydrologic science challenges from the CUAHSI Science Advisory Team:

1) process-based linkages and feedbacks within the water cycle as a function of environmental change;
2) interactions between the biosphere and the water cycle; and
3) the human dimension for water cycle interactions with respect to water availability and demand, and the propagation of anthropogenic modifications to the water cycle.

needed additional support and expertise in terms of application, deployment, and data interpretation.

Based on the SAT and the 2005 survey findings, the HMF WC committee foresees that the investment in instruments should provide immediate and significant opportunities to address key hydrological science questions across a range of sites and watershed scales. They identified eight instrument characteristics required to accomplish this goal (sidebar 3).

SCIENTIFIC MOTIVATION. While identifying specific instrumentation is a desirable outcome, a guiding question at the forefront of HMF logic is, "What can be achieved based on this initiative that cannot otherwise be accomplished?" We recognize that our scientific perspective and the distance from which we observe the system's state and its processes often determine the choice of instrument and methodology used to measure it. Historically, the combination of space and time, which are commonly explored experimentally, have been constrained fiscally and technically [depicted by the blue spheres along the diagonal in Fig. 1 (cf. Grayson and Blöschl 2000; Sivapalan 2005)]. While these delineations are subjective, they serve to guide the reader in relating measurements to their hydrological scales of interest.

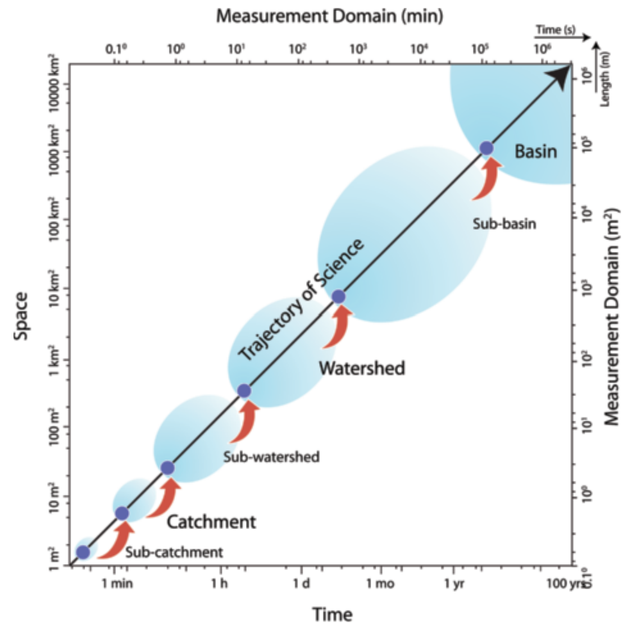

FIG. 1. Space and time representation of basin management unit scales. The domain is the sampling scale that might be necessary to resolve processes based on the watershed management unit scale. The blue ellipses represent classical experimental sampling domains. The red arrows suggest that HMF opportunities can support exploration of the scales of observation to the next higher and lower levels.

HMF INSTRUMENT CHARACTERISTICS

1) Science driven—Instrumentation should support the broad scientific themes identified by the Science Advisory Team. More specifically, the instrumentation should be explicitly linked to address multiple scientific hypotheses whose results can be readily communicated in the peer-reviewed literature.
2) Community identified—The choice of instrumentation should be identified via community input, including formal (e.g., surveys, workshops, committees) and informal (e.g., responses to draft white papers, communication with HMF PIs, and white paper committee members) processes.
3) Community resources—Instrumentation should be broadly available and applicable to researchers in the hydrological sciences community. Instruments that require routine, long-term deployment at single sites or watersheds are not considered to be community resources.
4) Enhances existing infrastructure—Significant measurement capabilities are already available at numerous experimental watersheds. Such watersheds can be expected to include stream gauges, meteorological stations, and precipitation gauges. HMF instruments are envisioned to extend and complement existing experimental watershed instrumentation and are anticipated to be capable of making measurements at the watershed scale (i.e., 1–1000 km^2).
5) Viable for campaign measurements—The instrumentation must be portable as necessary for deployment in multiple watersheds within the first 3-yr period, and all future endeavors.
6) Mature or rapidly emerging technology—The instrumentation must have a relatively short lead time between funding and deployment.
7) Novel technology—Routine access to instrumentation must be constrained due to costs, knowledge, or access. The HMF should provide instrumentation resources that are beyond the budget of a typical science proposal. Specific categories that might reasonably constitute a significant resource include instrument platforms, mobile "laboratories," and networked sensors. Instrumentation should not overlap with existing resources without a clear rationale.
8) Strong funding potential—Instrumentation should have strong funding potential through competitive proposals to existing funding programs and granting agencies.

Expanding our knowledge base across scales is not trivial, because watershed hydrology is complex with various degrees of organization (Dooge 1986; Grayson and Blöschl 2000; King 1990), such as river networks (e.g., Rodriguez-Iturbe and Rinaldo 1997), soils (Nielsen 1997; Nielsen and Wendroth 2003), soil water states (Vauchaud et al. 1985; Mohanty et al. 2000), latent and sensible heat fluxes (Brutsaert 1998), and the distribution of rainfall (Lovejoy and Mandlebrot 1985), and requires system measurements at fine levels of temporal and spatial resolution. Toward this end, a conceptual framework was developed to describe how a new measurement infrastructure would be used in the advancement of hydrologic science, which also included a description of hydrologic structure and process (Fig. 2a). We advocate here that HMF instrumentation should have the ability to establish links between scales of interest (depicted by red arrows in Fig. 1) and to measure processes of hydrologic significance shown in Fig. 2a off the current trajectory (i.e., the diagonal, Fig. 1).

While this background broadly defines the challenges that face the hydrologic sciences, the HMF WC committee asked, “What are specific areas of scientific inquiry that are critical to advance hydrology?” In order to support higher-order science questions and to advance modeling at the watershed scale, an absolutely fundamental need is to provide instrumentation that has the ability to close the water and energy budget at different scales. Key challenges in the water budget closure are the spatiotemporal characterization of soil moisture, groundwater movement and storage, and evapotranspiration.

Three additional challenges for the hydrologic sciences were identified by examining the measurements and research questions that were *not* historically made at scales corresponding to the upper-left-hand and lower-right-hand corners of Fig. 2 (i.e., short temporal scales among large spatial scales and small spatial scales among long temporal scales, respectively). First, a fundamental question at scales below the “diagonal” in the lower-right-hand corner, addresses how precipitation is partitioned to runoff, recharge, and evapotranspiration. Estimating the spatiotemporal controls on this question is key to understanding how droughts propagate, and how to better forecast water supply and flooding. Research also needs to make clear how tributaries add to the propagation of flooding (i.e., channel processes), with a specific emphasis on how the structural or orographic characteristics of a watershed contribute toward generating runoff. Improved strategies for partitioning precipitation will also require observations that can investigate the role that riparian vegetation plays in stream–aquifer interactions. Cross-scale observations are necessary to investigate the dependence of scaling relationships for floods on the scaling descriptions of topography, vegetation, precipitation, soil properties, and recharge. Overall, for hydrological extremes, research-

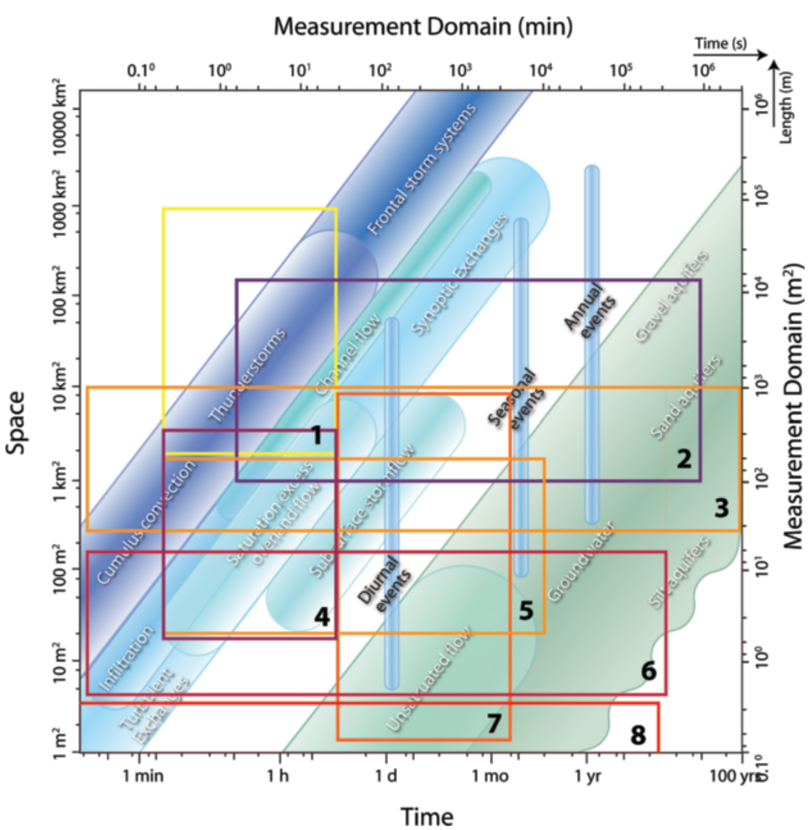

Fig. 2a. Schematic representing space and time process scales. The numbered rectangular boxes correspond to scales relevant for 1) urban environments–floods, 2) availability of water (drought), 3) climate change, 4) water supply–landscape productivity, 5) agricultural productivity, 6) transport processes, 7) biotic feedback mechanisms, and 8) site-specific sub-catchment-scale dynamics. The background time and space scales were modified from Bloschl and Sivapalan (1995; reproduced with permission).

ers still struggle to observe and differentiate between how surface and subsurface processes impact system response. Additional research questions regarding the partitioning of precipitation are outlined in Sivapalan (2003), and Jacobs et al. (2006) discussed other research questions in related disciplines.

The second challenge area focuses on hydrology, climate, and vegetation, that is, estimates of productivity through predicting the transformation of water at short time scales among large spatial scales (upper-left-hand corners of Figs. 1 and 2) and partitioning the sources of water to predict flow and storage, surface energy fluxes, and their relationship to ecosystem function and productivity (Black 1997). An example is outlined here. The typical approach for obtaining a watershed's soil–water balance is to measure soil water content and energy balance components in a *lumped* or *distributed* design. Meteorological data used to calculate actual evapotranspiration are often obtained from a station located at a considerable distance from the watershed. An implicit assumption is typically made that there is hydrological similarity in space as well as between the local and watershed scales. This assumption implies that within- and among-scale variability is known and accounted for, that is, differences between representative source areas for the measurements. Violations of this assumption are often key issues at research sites. For example, spatial variability in evapotranspiration may be linked to differences in soil water status and mechanisms of atmospheric transport, but these linkages cannot be verified with "undersampled" or spatially disjunct measurements within a watershed. Determining the structure among local soil water status, evapotranspiration, transport mechanisms, and vegetation relies on the ability to first measure the spatial variability in water vapor flux at short time intervals over relatively large source areas and sensor footprints (cf. Loescher et al. 2006).

The third challenge area, flooding and urban water dynamics, requires measurements corresponding to those made above the diagonal in the upper-left-hand corner of Fig. 2 (i.e., short temporal scales among large spatial scales). Flooding events exhibit the strong spatial and temporal variability of water storage and flow that occurs at relatively short time scales and intermediate spatial resolutions. These events have significant impacts on watershed function through channel evolution, lateral connectivity, and nutrient transport. Existing instrumentation networks, traditional measurements, and experimental approaches are currently inadequate to rapidly deploy instruments capable of sampling at the appropriate scales. While management of water resources is critical in highly populated regions, direct hydrologic measurements in urban watersheds are surprisingly sparse. Having the ability to characterize the complex spatial structure of urban floods at short time scales is a critical first step in predicting how water moves through heavily developed and rural environments alike.

PROPOSED WATER CYCLE INSTRUMENTATION. There are the following three categories

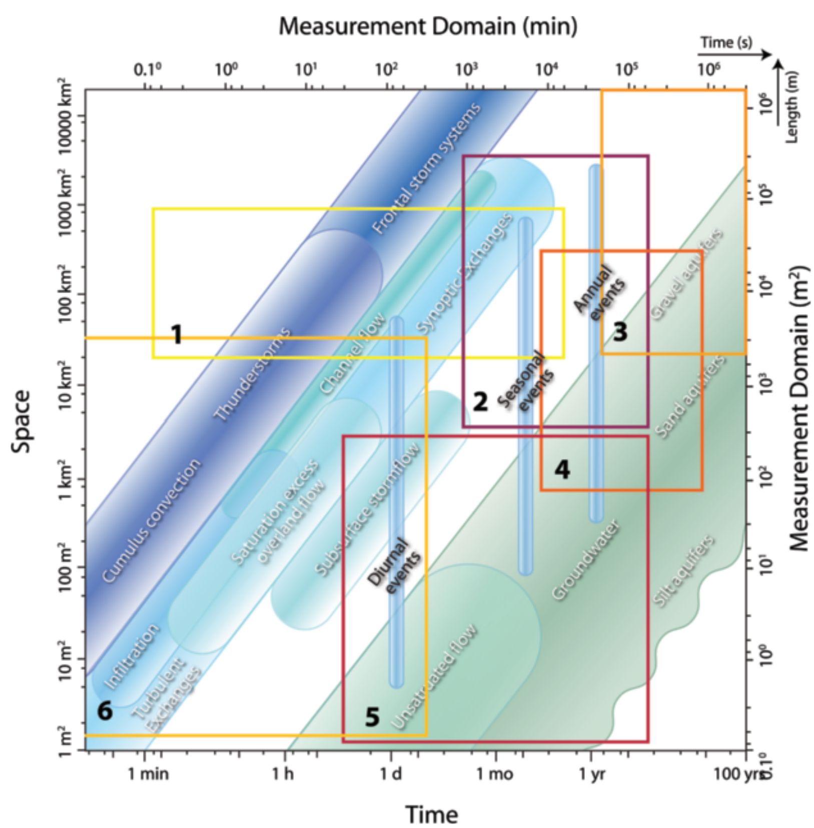

FIG. 2b. Schematic representing space and time process scales. The numbered rectangular boxes correspond to scales over which 1) x band, 2) lidar, 3) large aperture scintillometry and SODAR, 4) eddy covariance and isotope sensor, 5) networked sensors, 6) time-domain reflectometry and GPR operate. The background time and space scales were modified from Bloschl and Sivapalan (1995; reproduced with permission).

Table 1. Proposed water cycle instrumentation by discipline and category, where SWE = snow-water equivalent, ICOS = integrated cavity output $^{16}O/^{18}O$ spectroscopy, and TDEM = time domain transient electromagnetic surveys

Discipline	Single instrument	Mobile laboratory	Suites of networked/ wireless sensors
Rainfall	X-band polarimetric radars	Truck mounted X-band radar(s)	Disdrometers Paired network of tipping-bucket rain gauges
Snow	Airborne lidar Sled-mounted lidar	Snow pillows Flat-band snow sensors	SWE Albedo, acoustic depth sondes, energy balance
Evapotranspiration	Water vapor lidar	Sodar RASS, large-aperture scintillometry, and eddy covariance coupled with ICOS	Surface soil and atmospheric micrometeorological sensors
Hillslope flow processes		Laser isotope spectroscopy	Collection of water samples Coupled sensor sampler devices
Vadose zone transport	Passive microwave	Vadose zone lab with a host of measurement capabilities	Soil moisture sensors
Groundwater processes	Airborne high-resolution TDEM Airborne lidar	Ground-penetrating radar Electromagnetic induction	Ability to install and monitor a network of groundwater wells

of instrumentation that can reasonably address the experimental challenges described above: 1) individual instrument platforms, 2) mobile laboratories, and 3) suites of networked sensors (see Table 1 and cf. Fig. 2b). Jacobs et al. (2006) describe in detail the rationale for specific instrumentation, measurement accuracy and precision, data processing requirements, working conditions and environment, deployment requirements (required setup time, minimum deployment time, operating constraints), costs (off shelf, modifications, support for deployment), feasibility (time, logistics, scheduling), support requirements, development stage (status, needs, required modifications), and the potential scale it can measure in the space–time domain.

In addition to ground-based instrumentation, remote sensing capabilities emerged as a critical need. Access to a range of airborne remote sensing instruments are called for to provide measurements at intermediate scales and to support ground surface networks. Although the development of new satellite-borne sensors are currently outside the HMF's experimental purview, parallel CUAHSI activities seek to develop new software tools to access remote sensing data relevant to the hydrological sciences.

The breadth of scientific inquiry will be better served if suites of instruments can be deployed in concert with other in-house measurements within a single watershed. A suitable community instrumentation resource would enable the comprehensive examination of robust scientific hypotheses and robust estimation of parameters to be made through the deployment of these suites across numerous watersheds. Priority instruments are those that best meet the eight HMF criteria (see sidebar 3) and can advance measurements in more than one challenge area. Through community input and the criteria described above, several instruments were identified. These include networked sensor arrays, mobile precipitation radar, evapotranspiration flux suites, electromagnetic surveys, and passive microwave sensors. All suites of instruments have a high likelihood of an immediate impact on future hydrological research. The development of electromagnetic surveys of subsurface flow properties is clearly valuable; however, that instrumentation was outside the scope of the water cycle HMF group. It should be noted that passive microwave sensors are likely to take a long time between funding and deployment, because they are limited in their commercial availability and would have to be extensively tested before deployment.

The HMF biogeochemistry and geophysics working groups also identified numerous suites of instrumentation and resources to enhance current measurements, several of which are explicitly included in the HMF WC proposed suites of instrumentation. This implies a direct connection to the broader science themes and questions addressed by our companion HMF working groups. Enhancing these connections further by either expanding the scope of existing suites or by creating new suites would serve the hydrologic sciences well.

This work focuses on the rationale and processes to decide which suites of instrumentation best serve the future of hydrologic science. However, we cannot overly stress the importance of ongoing community outreach and education in this endeavor. To encourage interdisciplinary activities, we plan on conducting full-day HMF orientation and training sessions at national society meetings, and have mechanisms in place to foster student and postdoctoral participation, particularly for those in under-represented groups. We also plan on conducting independent, outside evaluations (about every 3 yr) to ensure that HMF activities are responsive to the community needs.

IMPLEMENTATION. The proposed governance structure for CUAHSI HMF will be decentralized (i.e., nodes), with universities hosting a particular suite of instrumentation and coordinating the technical expertise required to acquire and interpret data. Acquisition of the instruments and development of a university node would be the responsibility of a (group of) principal investigator(s), who would be funded through competitive granting in collaboration with CUAHSI. Each node will operate under a common set of guidelines for operation, access, and deployment of instrumentation and for issues such as data ownership and intellectual partnerships associated with the development of collaborative research relationships. During the inception of the HMF, these nodes will most likely operate without a central facility, although one may be created once a critical number of administrative activities have been identified that require efficient and centralized operation. Once established, the center may also undertake other nonadministrative activities, such as housing instrumentation that does not require technical expertise, research and development, or other activities that are not yet contemplated.

The HMF's mission is to provide access to emerging technologies to support tomorrow's science. Collaboration and community input have guided the process to date and will continue to be critical to achieving the HMF mission. There are numerous opportunities to engage with existing and planned HMF activities, including the establishment of collaborative partnerships across disciplines within and outside of CUAHSI initiatives, leveraging existing expertise and instrumentation within Earth system science communities, and accessing the proposed HMF Water Cycle instrumentation. Interested scientists can obtain further information about the technologies and upcoming events from the CUAHSI Web site (www.cuahsi.org) or by contacting the HMF PIs.

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