Enhanced Water Cycle Measurements for Watershed Hydrologic Sciences Research

A report prepared for the

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

by

J. Jacobs, University of New Hampshire
W. Krajewski, University of Iowa
H. Loescher, Oregon State University
R. Mason, USGS Office of Surface Water
K. McGuire, Plymouth State University
B. Mohanty, Texas A & M
G. Poulos, NCAR
P. Reed, Pennsylvania State University
J. Shanley, USGS
O. Wendroth, University of Kentucky

(HMF) Support
D.A. Robinson, Stanford University

May 2006
Acknowledgements

This material is based upon work supported by the National Science Foundation under Grants 03-26064 and 04-47287. Any opinions, findings, and conclusions or recommendations expressed in this material are those of the authors(s) and do not necessarily reflect the views of the National Science Foundation.
# Table of Contents

Table of Figures ........................................................................................................... ii
Preface ............................................................................................................................... iv
1. Introduction.................................................................................................................. 1
   1.1. CUAHSI HMF Vision for a Community Instrumentation Resource .................. 1
   1.2. CUAHSI SAT Themes ......................................................................................... 1
   1.3. Survey Results .................................................................................................... 2
   1.4. Characteristics of Priority Instruments ................................................................ 2
   1.5. Document Overview ........................................................................................... 3
2. Current Status of Experimentation to Advance Water Cycle Science .......... 4
   2.1. Water Cycle Experimentation Challenges .......................................................... 4
   2.2. Spatiotemporal Sampling Domain ...................................................................... 5
   2.3. Process Scale and Sampling ............................................................................. 6
   2.4. Hydrological Science Challenge Areas .............................................................. 7
   2.5. 0th Order Hydrologic Science Challenge Area ................................................. 9
3. State of Technology in Water Cycle Measurement ........................................... 10
   3.1. Rainfall .............................................................................................................. 11
   3.2. Snow and Snow Melt ....................................................................................... 14
   3.3. Evapotranspiration ......................................................................................... 17
   3.4. Hillslope Processes and Stream Flow Generation ............................................. 24
   3.5. Streamflow ...................................................................................................... 27
   3.6. The Vadose Zone ............................................................................................. 31
   3.7. Groundwater .................................................................................................... 33
4. Proposed Instrumentation Suites ............................................................................. 39
   4.1. Water Supply/Droughts/Flood Forecasting ......................................................... 40
   4.2. Hydrology and Climate/Agricultural and Ecosystem Productivity .................... 43
5. Potential CUAHSI Water Cycle Instrumentation Synergies .............................. 47
   5.1. Large Instruments (LIDAR and Passive Microwave) .......................................... 47
   5.2. National Center for Atmospheric Research (NCAR) .......................................... 50
   5.3. USGS Hydrologic Instrumentation Facility (HIF) .............................................. 51
   5.4. National Center for Airborne Laser Mapping (NCALM) .................................... 52
   5.5. Watershed Networks ....................................................................................... 52
   5.6. The Florida Coastal Monitoring Program (FCMP): ............................................ 53
   5.7. Field Campaigns, Past and Future ..................................................................... 54
   5.8. Collaborative Large-Scale Engineering Analysis Network for Environmental Research (CLEANER) .............................................................................. 55
   5.9. National Ecological Observatory Network (NEON) .......................................... 55
6. Strategic plan .............................................................................................................. 56
   6.1. Priority Instrumentation ..................................................................................... 56
   6.2. HMF Challenges ............................................................................................... 57
References ...................................................................................................................... 59
Table of Figures

Figure 1. Space and time representation of watershed management units 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 exploring the scales of observation to the next higher and lower levels.................................................................4

Figure 2. Schematic representing space and time process scales. The numbered rectangular boxes correspond to scales over which 1) urban environments/floods, 2) drought, 3) climate change, 4) water supply/landscape productivity, 5) agricultural productivity, and 6) transport processes operate. Associated numbers are located in the bottom right-hand corner of each box.......................5

Figure 3. Selected soil hydrology studies and their approximate associated space and time scales. Cited references are not intended to completely represent the literature published with regard to the subject matters........................................................................................................................................6

Figure 4. Illustration of SkyTEM adapted from (Sorensen and Auken 2004)............................35

Figure 5. Left the HELIMAP LIDAR scanning system in detail, to the right the system helicopter mounted........................................................................................................................................36

Figure 7. Schematic representing space and time process scales. The numbered rectangular boxes correspond to scales over which 1) x-band, 2) LIDAR, 3) LAS/SODAR, 4) EC/isotope sensor, 5) networked sensors, 6) TDR, and 7) GPR operate. Associated numbers are located in the bottom left-hand corner of each box........................................................................................................................................39

Figure 8: (a) Climate flux array, (b) Evaporation-Transpiration-Recharge Array, (c) Differential Stream-Reach flux array, and (d) Hillslope flux array. Adapted from (Reed et al. In Review).........42

Figure 9. Examples of tower systems, (a) the USA’s ComRAD (Combined Radar/Radiometer) mounted on an 18-m hydraulic boom truck; (b) Europe’s EMIRAD polarimetric radiometer deployed on a 38-m tower (Source O’Neill,(2005) NASA)........................................................................................................48

Figure 10: The promise of high resolution water vapor DIAL measurements from the recent International H2O Project 2002 (IHOP). Pictured are measurements of atmospheric boundary layer water vapor mixing ratio and Doppler lidar vertical velocity measurements (top two figures) and the resulting vertical water vapor fluxes (for details see Weckwerth and Parsons (2006) and www.eol.ucar.edu/dir_off/projects/2002/IHOPwsOct03/kiemle.ppt...................................................49

Figure 11. USDA Agricultural Research Service watersheds in the US........................................53

Figure 12: An FCMP tower deployed before hurricane Frances landfall (left), and a house in the Panhandle being readied to collect pressure and wind velocity data prior to Ivan (right). (Source: K. Gurley).................................................................54
Table of Tables

Table 1. Proposed instrumentation by discipline and category. .......................... 10

Table 2. Available L Band Ground-Based Microwave Instruments
(source O’Neill) ........................................................................................................ 48

Table 3. Available LIDAR Instruments (source: G. Poulos) ................................. 50
Preface

The main purpose of this report is to provide a vision for the use of direct measurement instrumentation in watershed scale hydrological research. The aim of the report is to identify instrumentation that could significantly advance this vision for water cycle research in hydrology during the next five years. Most of the emphasis is on high tech instrumentation and networked systems that are beyond the current capability of individual PI's to implement. These systems such as mobile LIDAR and rainfall radar could revolutionize the spatio-temporal data collection for watershed research. This report describes these instruments and provides examples of their use. It also considers the deployment and costs associated with data collection, as well as examining the interpretation of data, and how measurements and modeling can be synergistically linked.

The HMF Water Cycle advisory group was established in the summer of 2005; it is a national committee composed of senior scientists with expertise spanning hydrology, soil science, and atmospheric science. The team includes university researchers and members of the US Geological Survey.

The HMF Water Cycle advisory group is led by Jennifer Jacobs (University of New Hampshire) and consists of Witold Krajewski (University of Iowa), Henry W. Loescher (Oregon State University), Robert Mason (USGS Office of Surface Water), Kevin McGuire (Plymouth State University), Binayak Mohanty (Texas A & M), Greg Poulos (NCAR), Patrick Reed (Penn State), Jamie Shanley (USGS) and Ole Wendroth (University of Kentucky).

The group met formally in February 2006 following bi-weekly teleconferences. This report is the result of nearly 6 months of discussion and dialogue.

The concept to emerge from this work is for the HMF WC to 1) develop timely, emerging suites of technologies that are well suited to couple the water cycle subdisciplines, and 2) advance science questions that are currently challenged due to limited spatial and temporal measurement resolution. We envision that the most significant advances will require the parallel deployment of multiple instruments in a campaign style deployed, in turn, across multiple watersheds. This concept assumes that instrumentation decisions are explicitly informed by priority science questions and defined challenges in our ability to measure water resources.

This report identifies three broad research focus areas and required instrumentation suites: 1) Water Supply/Droughts/Flood Forecasting, 2) Hydrology and Climate/Agricultural and Ecosystem Productivity, and 3) Opportunistic Measurements - Extreme Events (Prediction and transformation). The third area, Opportunistic Measurements, has considerable significance and can transform the science of hydrology. However, a significant return on investment will require additional planning and engagement with the community. Immediate opportunities exist for the first two focus areas. Initiatives to develop collaborative instrument proposals between PIs and the HMF should move forward as rapidly as possible. A parallel effort should also be conducted by the HMF to develop the infrastructure to support successful acquisition of equipment.
1. Introduction

1.1. CUAHSI HMF Vision for a Community Instrumentation Resource

The Hydrologic Measurement Facility (HMF) is being established to facilitate access to advanced instrumentation and expertise in support of hydrological sciences (broadly defined) and large-scale research on watershed hydrology. The coordinated effort has been organized around three general topic areas: water cycle (WC) sciences, geophysics, and biogeochemistry. The preliminary task of the HMF coordinating group is to seek input from the hydrological science community to determine needs that the HMF could meet and innovate ways to provide this support without creating competition for individual PIs.

The HMF WC committee was formed to identify instrumentation and technologies that would significantly enhance the measurement of fluxes and stores in the water cycle. The WC focus group has considered the Science Advisory Teams research themes, synthesized survey results from the research community, created a conceptual framework to identify impediments and opportunities in hydrological sciences through enhanced measurements, and identified emerging water cycle instrumentation and potential synergies among these instruments. In addition, numerous instrumentation opportunities may exist through partnerships external to CUAHSI. A preliminary review and discussion with some potential partners was conducted.

1.2. CUAHSI SAT Themes

The CUAHSI Science Advisor Team (SAT) has identified three themes that broadly characterize the science challenges for predicting, detecting, and managing water in a changing environment. These themes are 1) 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. The SAT specifically recognizes that modifications to observation strategies are required to address emerging science challenges. The strategy includes enhancements to existing long-term observatories, development of new observatories, and making observations in a campaign style approach. Examples of campaigns style measurements include the Soil Moisture Experiments (SMEX), the North American Monsoon Experiment (NAME), the Cold Land Processes Experiment (CLPX) and the Semi-Arid Land Surface-Atmosphere (SALSA) program campaigns. The HMF is best suited to support the proposed campaign style approach that includes opportunistic measurements as well as planned campaigns. Opportunistic campaigns are envisioned which deploy instrumentation to monitor hydrological events having significant flux gradients.

Several aspects of the SAT’s observing strategy specifically informs the prioritization of HMF WC instrumentation. The call for multi-scale observations requires the acquisition of instruments capable of providing distributed measurements beyond existing infrastructure and capabilities. The strategy of multidiscipline observations calls for suites of complementary instruments that can be deployed simultaneously to make measurements at comparable scales. The SAT’s concept of adaptive design suggests that a priori deployment strategies should transition to a real-time sampling strategy that is responsive to
preliminary measurements and adaptive over measurement campaigns. To accomplish this, connections between installation and monitoring should be enhanced and constraints implicit in hardware/network monitoring should be reduced. Opportunistic campaigns encourage rapid response through mobile platforms, advance reconnaissance, and agency partnerships.

1.3. Survey Results
The CUAHSI HMF conducted a survey from November 2005 to January 2006 to gain a community perspective on the measurement, instrumentations, and support needs within the hydrological science community (Robinson et al., 2006). The survey, to be published in full on the CUAHSI website (www.cuahsi.org), assessed the level of support for community instruments and support, and requested input on technologies and methodologies that could make major advances in the hydrologic sciences. Respondents were asked what was most needed to make progress in hydrologic sciences. Of the 23 questions with possible scores ranging from -100 to 100 (positive indicating support) there was overwhelming support (>75%) for four major initiatives:

1. Improving the integration between measurement and modeling methods (80.6%)
2. Improving spatial resolution of measurements (79.7%)
3. The ability to make more/better measurements through distributed sensor networks (77.3%)
4. Improving our ability to measure and quantify the subsurface (76.4%).

There was more support for providing access to equipment costing over $20,000 with accompanying technical support for both deployment and data interpretation than there was for standard equipment. Respondents were quick to identify field deployable equipment that could augment ongoing studies. Asked what sort of supported equipment they would like to have access to, repeated responses included: atmospheric profilers (RASS, LIDAR, SODAR-RASS), geophysical equipment both ground based and airborne, ground penetrating radar (GPR) and electromagnetic induction (EMI) sensors being most commonly mentioned, weather radar, soil moisture sensing capability and atmospheric flux towers. Importantly, respondents also pointed out that for success to occur, the required equipment needed additional support in terms of application and data interpretation. This effort should be directed towards the collection of high quality data sets that become a community resource.

1.4. Characteristics of Priority Instruments
The HMF should invest in instrumentation that can provide immediate, significant opportunities by addressing key hydrological science questions across a range of watershed scales. A number of instrument characteristics are required to accomplish this goal were identified and are as follows:

1. Science Driven – Instrumentation should support scientific inquiry that is aligned with the broad 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 – Potential instrumentation priorities should be identified via community input including formal (e.g., surveys, workshops, committees) and informal (e.g., response to draft white papers, communication with HMF PIs, 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 at present.

4. Enhances Existing Infrastructure – Significant resources are already available at numerous experimental watersheds. Such watersheds can be expected to include stream gages, meteorological stations, and precipitation gages. 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 km²).

5. Viable for Campaign Measurements – The instrumentation must be portable as necessary for deployment in multiple watersheds within the first 3-year period, and all subsequent periods.

6. Mature or Rapidly Emerging Technology – The instrumentation must have a relatively short lead time between funding and deployment. Again, instrumentation must be deployed in multiple watersheds within the first 3-year period and all subsequent periods.

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 rational.

8. Strong Funding Potential – Instrumentation should be have strong funding potential fundable through competitive proposals to existing NSF funding programs and other grant providing agencies.

1.5. Document Overview

The research opportunities compiled in this report regard hydrologic research within the Hydrologic Measurement Facility (HMF), and are derived from a water cycle viewpoint. The following sections present a conceptual plan for the water cycle sciences’ (WC) contribution to the HMF effort. The conceptual plan is informed by the SAT themes and the HMF Survey results and constrained by the characteristics of priority instruments. The WC group strongly advocates that instrumentation serves to advance science, and that the choice of instrumentation must be explicitly informed by priority science questions. The material that follows presents the core HMF WC concepts in two main sections. Section 2 broadly presents the current practice in experimental hydrology and identifies specific challenge areas. Section 3 proposes specific instruments to address challenges identified in each hydrological process area. The remainder of the document addresses potential synergies in Section 4 and a strategic plan in Section 5.
2. Current Status of Experimentation to Advance Water Cycle Science

2.1. Water Cycle Experimentation Challenges

A guiding principle maintained throughout this report, and a question at the forefront of HMF logic is, “What can be achieved based on this initiative that cannot otherwise be accomplished?” To answer this question, we must recognize that our perspective and the distance from which we observe the system’s state and its processes determine the choice of instrument to measure it. Hydrologic processes are governed by first principle continuity relationships that are usually difficult to solve. Thus, the practical application of these relationships requires robust parameterizations of the underlying structure and function. Acknowledging the time-space variability of landscape characteristics and climate in space and the transport-determining state variables precludes the simplifying assumption of homogeneous geometry that underlies many attempts to describe water fluxes across different scales. Challenges result from the knowledge that hydrologic parameters are a function of scale and that the appropriate scale depends on the question or process under consideration (Brutsaert 2005).

The underlying space-time domain shown in Figure 1 provides a framework for comparing hydrological processes, water resource applications, and measurement capabilities. For convenience, the Center for Watershed Protections (CWP) definitions of watershed management units (watershed vulnerability analysis, 2002), with their approximate corresponding areas; basin (2,500–25,000km²); sub-basin (250–2,500km²); watershed (80–250km²); sub-watershed (1–80km²); catchment (0.1–1km²) are adopted. Though these delineations are subjective, they guide the reader in relating measurements to their hydrological scales of interest. Figure 2 identifies some hydrological processes and applications by their space and time scale using a space-time diagram.

![Figure 1. Space and time representation of watershed management units 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 exploring the scales of observation to the next higher and lower levels.](image-url)
2.2 Spatiotemporal Sampling Domain

The portion of the spatiotemporal domain of water cycle scientific research – science that is commonly explored experimentally - is illustrated by the blue spheres in Figure 1. That water cycle science has been unable to expand outside these bounds is primarily driven by the limits of current observational platforms and methods. A continuum of relevant structure and process oriented studies (Figure 3) can provide the basis of future experimental design. However, the examples do not fulfill the spectrum of originality and completeness. As an example, to understand very small scale processes, Or and Tuller (2000) used solid particle surface, wetting angle, and water film thickness to calculate water flow rates, Uijlenhoet et al. (2003) discerned raindrop size distributions in extreme rainfall events, and Harrington et al. (1996) characterized snow melt at laboratory scales. At the next higher scale of space-time (i.e., between 1 m$^2$ and 100 m$^2$ and < 1 day to several weeks) are investigations of water transport phenomena in water-repellent soils (Dekker et al. 1994), preferential flow and transport (Hangen et al. 2005), and fundamental studies of plant water uptake (Bruckler et al. 1991). Watershed variability and processes relevant at day to month time scales are characterized by hillslope transport (cf. Asano et al. 2002, McGuire et al. 2005), evaporative fluxes from homogenous landscapes (cf. Whitfield et al. 2006), and snowmelt (Sommerfield et al. 1994). Lastly, watershed scale science may include analysis of annual water cycles (cf. Moog and Whiting 2002), characterization of storm structure (cf. Steiner et al. 1995), or regional discharge records over decadal scale (cf. Peterson et al. 2002). The diagonal space-
time arrangement of the references implies that, up to the present, processes over relatively large spatial domains remain extremely difficult to study at small temporal resolution, and that long temporal processes have not been investigated at small spatial domains.

2.3 Process Scale and Sampling

Expanding a knowledge-base across scales is not trivial, as watersheds are “complex systems with some degree of organization” (Dooge 1986). Examples of organization are found everywhere in hydrology including river networks (e.g., Rodriguez-Iturbe and Rinaldo 2000), soils (Nielsen and Wendroth 2003, Wendroth et al. 2006), soil water state (Vauchaud et al. 1985), latent and sensible heat fluxes (Brutsaert 1998), and rainfall (Lovejoy and Mandelbrot 1985). To understand the regular geometric patterns may simplify analysis and prediction through the understanding of dominant processes (Grayson and Bloschl, 2000; Sivapalan 2005). Thus, the ability to diagnose change in a system over space and time is dependent on the identification of any existing organization. This identification implies the need to observe the system’s state at the elemental level, i.e., at fine levels of temporal or spatial resolution. The extent of the areal expanse or time duration over which observations are made sets an upper limit in our ability to identify any differences (King 1990). Within this extent or domain, the continuity of measurements needs to be assessed over small increments to discern whether any underlying organization is intrinsically linked to the experimental design and in our ability to measure the within scale variability.

The precision and accuracy of measured quantities can also change as a function of how biotic and abiotic controls change...
across time and space. Hence, measurement schemes have to be designed to capture the inherent variability in the quantities of interest. For example, time series datasets of river level sampled every month for ten years may result in a temporal correlation length that differs from that of the same variable sampled on a daily basis over six months. In another example, accuracy of soil carbon respiration rates differ across time and space dependant on seasonal interactions between soil temperature and water content (Loescher et al. 2006a). In this case, the measured coefficient of variation significantly increased during spring snow melt and after large rainfall events. Moreover, each particular instrument has its own time constants and random error due to its ability to process an electronic signal. Experimental design and the choice of an appropriate instrument to measure a desired quantity also need to assess suitable averaging times to minimize instrument bias due to time constants and random error while maximizing its ability to measure the natural variability of the measured quantity across the desired spatiotemporal scales (cf. Loescher et al. 2005, Loescher et al. 2006b).

When analyzing processes over a range of spatial and temporal scales the concept of a representative elementary volume (REV) being developed for a particular measurement scale needs to be expanded by space and time components (Baveye and Sposito 1985). The validity of the concept of effective parameters relevant at a particular scale has to be thoroughly questioned, as their derivation depends on a priori averaging of variables for the inverse estimation (Feddes et al. 1993a, b). Rather than focusing on local averages and effective parameters, a challenging task in analyzing hydrologic processes is the identification of appropriate state variables measured at the land surface, and their cross correlation structure to soil water status and transport, including evapotranspiration, and unsaturated flow at different space-time scale combinations. As important as determining magnitudes of system’s rates of changes, fluxes and transport rates themselves are determining the impact of data aggregation and sampling density on the spatial estimation (Vucetic et al. 2000). Having identified the patterns of relevant state variables, a key issue of aggregating information from small to large scales is resolved. Therefore, the conceptual framework for upscaling processes exists and awaits application to specific landscape research questions (King 1990).

2.4 Hydrological Science Challenge Areas

The scale variance of processes and the REV concept manifest the importance of not only studying a process at a particular combination of spatial and temporal scales, but also estimating processes across to the next higher and lower spatial and temporal scales. As scales transition from the lower left-hand to the upper right-hand corner of the diagram (Figures 1, 2, and 3), the less knowledge exists on how to integrate processes relevant at small space-time scales to larger space-time scales, and the more it is assumed by investigators that processes at sub-domains occur homogeneously. This assumption has not been validated experimentally, nor has there been the intellectual opportunity to design such experiments for validation. It is likely that integrating measurements into a comprehensive understanding at larger space-time scales will have to include some combination of measurements and model results. New tools and measurement schemes have to be developed to identify what information is
gained, and what is lost, when crossing different space-time-scale combinations and characterizing processes across a range of scales. Two promising modeling approaches have emerged. First, the optimization of model parameters using Kalman filter approaches. Second, the use of mean and variance estimates at one scale to constrain the behavior of a process at associated scales, i.e., data assimilation. Identifying how data at one scale can be used to couple processes at associated scales, remains largely unexplored in all the hydrologic sciences. To address these challenges, the HMF seeks to provide opportunities to simultaneously sample at multiple scales, expand the existing measurement scales as depicted in Figure 1, and advance our knowledge in this area.

The hydrologic sciences have not historically tackled questions at scales corresponding to the upper left-hand and lower right-hand corners of Figure 2. This suggests that highly important questions regarding water dynamics as a function of vegetation, soil, and climate organization remain open. There are two areas of space-time-scale combinations that have hardly been approached, partly due to the limited capability in readily accessible instrumentation packages. Many applications of hydrological sciences research, including droughts, climate change, water supply, landscape productivity and transport processes are located below the “diagonal” in the lower right hand corner in this domain. Hydrologists have typically not had the opportunity to explore processes that occur over large areas, i.e., from the small catchment to watershed scale that occur in relatively short periods of time.

An example is briefly outlined here. The usual approach of 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. These calculations are made without knowing whether observations of soil water status are spatially linked to the weather station measurements. Moreover, evapotranspiration spatial variability 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 watershed measurements. Insight will result from investigating the relevant variable. The ability to derive the structure between local soil water status, evapotranspiration, transport mechanisms and vegetative biota to properties within soil mapping units relies on the ability to first measure spatially distributed water vapor fluxes at short time intervals over a relatively large area.

Flooding and urban water dynamics are synergistic research opportunities above the diagonal in the upper left-hand corner of Figure 2. Flooding events exhibit strong spatial and temporal variability of water patterns that occur 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 appropriate scales. While management of water resources are critical in highly populated regions, direct hydrologic measurements in urban watersheds are surprisingly sparse. Having the ability to characterize the complex spatial structure at short time scales is a critical first step
in predicting water dynamics for suburban and urban environments.

Other issues above the diagonal are related to the slow, continual, and episodic development of local watershed properties occurring within the decadal timescale. Besides existing long-term research plots, new long-term experiments and monitoring programs need to be established. The analysis of decadal scale datasets with various applied statistical methods can identify temporal covariant- and temporal coherent structures, which can allow us to quantify the long-term (i.e., low frequency) controls on slowly evolving watersheds. Although gradual, evolution of watershed patterns associated with the upper left-hand corner of the diagram in Figure 2 deserves attention, they are not considered to be a first priority for the HMF.

2.5 0th Order Hydrologic Science Challenge Area

The science questions identified above may be considered to be first order science questions in that they are critical to advance hydrology. Closing the water budget is considered to be a 0th order question that is absolutely fundamental to develop closure relationships, to support identified higher order science questions, and to successfully advance watershed modeling. However, there are significant gaps in our ability to close the water budget at all space-time scales. Key challenges in the water budget are characterizing soil moisture, groundwater storage, and evaporative fluxes. The following sections’ specific questions, instrumentation, and measurements should be considered in light of opportunities to improve water budgets as well as target higher order questions. The HMF should embrace the opportunity to look at systems as a whole and should prioritize instrumentation suites that can reduce the uncertainty of poorly characterized water budget components.
3. State of Technology in Water Cycle Measurement

The hydrological sciences require improved spatial measurements at watershed and subwatershed scales to advance our understanding of patterns, process, and function. If instrumentation access is constrained due to costs, knowledge, or access, the HMF can facilitate routine access to instrumentation capable of making such measurements. Three categories of instrumentation that may reasonably support studies made above the diagonal are individual instrument platforms, mobile “laboratories”, and networked sensors. Potential suites of instruments were identified by the HMF WC group, Table 1. Here, instrumentation is described according to major WC processes, and includes details on 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. The breadth of scientific inquiry into processes will be better served if suites of instruments can be deployed in concert at a single watershed. A community instrumentation resource would enable the examination of robust scientific hypotheses and robust estimation of parameters to be made throughout the deployment of these suites across numerous watersheds.

<table>
<thead>
<tr>
<th>Discipline</th>
<th>Single Instrument</th>
<th>Mobile Laboratory</th>
<th>Networked/Wireless Sensors</th>
</tr>
</thead>
<tbody>
<tr>
<td>Rainfall</td>
<td>X-Band Polarimetric Radars</td>
<td>Truck mounted X-Band Radar</td>
<td>Disdrometers</td>
</tr>
<tr>
<td></td>
<td></td>
<td></td>
<td>Paired Network Tipping Buckets</td>
</tr>
<tr>
<td>Snow</td>
<td>Airborne Lidar Sled-mounted radar</td>
<td>Deployable snow pillows Flat band snow sensor</td>
<td>SWE, albedo, temperature, acoustic depth sondes, energy balance</td>
</tr>
<tr>
<td>Evapotranspiration</td>
<td>Water Vapor Lidar</td>
<td>Module: SODAR-RASS, LAS, EC, ICOS</td>
<td>Meteorological Data</td>
</tr>
<tr>
<td>Hillslope Flow Processes</td>
<td></td>
<td>Laser isotope spectroscopy</td>
<td>Collection of water samples Coupled sensor sampler devices</td>
</tr>
<tr>
<td>Streamflow</td>
<td>PIVs</td>
<td>Remote Control Boats Hydroacoustic Instruments</td>
<td>Visible/IR Cameras</td>
</tr>
<tr>
<td>Vadose Zone Transport</td>
<td>Passive Microwave</td>
<td>Vadose zone monitoring lab</td>
<td>Soil moisture sensors</td>
</tr>
<tr>
<td>Groundwater Processes</td>
<td>Airborne TDEM Airborne Lidar</td>
<td>Mobile lab. Geophysics (GPR, Electrical)</td>
<td>Groundwater Wells</td>
</tr>
</tbody>
</table>

Table 1. Proposed instrumentation by discipline and category. Acronyms are defined in detail below.
3.1 Rainfall

Rainfall is the liquid form of precipitation that results from condensation of atmospheric water vapor (Snowfall is treated separately in the next section). Rainfall is the main means of delivery of fresh water supply to surface and subsurface reservoirs over much of the land portion of the Earth. It is also a main source for many natural hazards such as flash-floods, floods, landslides, and debris flows. Thus, rainfall plays an important role in studies of rainfall-runoff processes, erosion, vegetation growth, water and energy balance, and water resources management and interaction with the human dimension. Rain gauge networks provide surface-based information that has great importance to primary research activities and managers of water resources alike.

Physics of the atmospheric processes leading to the formation of rainfall are discussed in many references (e.g., Wallace and Hobbs 2006, Pruppacher and Klett 1997, Smith 1993) yet the skill to make quantitative observations and predictions of these processes remains limited. Processes leading to rainfall vary across many spatial and temporal scales, from isolated convection due to differential heating of the surface with a scale of several square kilometers, to organized convection due to an unstable atmosphere over areas of thousands of square kilometers, to widespread rainfall from synoptic scale frontal systems. Vertical motions of the air masses, availability of water vapor, and presence of cloud condensation nuclei are the necessary conditions for the occurrence of rainfall. Numerically-based prediction models for rainfall formation, known as cloud models, involve solutions of large sets of deterministic partial differential equations responsible for conservation of mass, momentum, and energy, and the evolution and interactions of cloud and precipitation particles. Temporal scales involved in storm formation and lifecycle range from tens of minutes to days.

Rainfall intensity, rate, and accumulation are known to vary significantly over a wide range of spatial and temporal scales. The relationships to scale rainfall have been investigated by many researchers (e.g., Zawadzki 1987, Schertzer and Lovejoy 1987, Gupta and Waymire 1990, 1993, Over and Gupta 1994, Deidda 2000, Pavlopoulos and Gupta 2003). The primary motivation for scaling is the need to downscale large scale precipitation predictions from the global climate models because rainfall-runoff processes are governed at different scales than atmospheric processes. While many studies have shown the utility of scaling of rainfall in space and time, linkages between the physical processes and the scaling relationships are not well established. The difficulty of this task has been demonstrated by several studies (e.g., Perica and Foufoula-Georgiou 1996, Harris et al. 1996, Georgakakos and Krajewski 1996, Nordstrom and Gupta 2003).

The inability to scale rainfall in space and time is primarily due to instrumentation limitations. Data from a single rain gauge, represents at best a limited area, only allows the investigation of temporal scaling (e.g., Georgakakos et al. 1994, Marani 2005). Precipitation radars have the ability to provide measurements at intermediate scales with resolutions to hundreds of meters in space and minutes in time. These scales can link point scale gauges to clustered rain gauge networks. This in turn, can understand and constrain radar-based estimate errors, an active area of research (Krajewski et al. 1996, Harris et al. 1997). The most common observational systems for rainfall amounts are rain gauge net-
works, weather radars, and weather satellites. Since the HMF WC focus is on ground-based systems, the proposed instruments are limited to new radar system concepts and technologies. Krajewski (2006) provide an overview of ground-based systems including networks of rain gauges, disdrometers, and vertically pointing radars.

Careful estimation of uncertainties is needed to scale from point sources to the spatial scale resolvable by radar. Rainfall estimates biases from point sources (e.g., tipping bucket gauges) have been characterized (Habib et al. 2001, Ciach 2003). The standard errors decrease with increasing quantities of rain and over longer time integrals. Wind can also cause an under estimation of rainfall rate (Habib et al. 1999, Sieck et al. 2006) yet this error is significantly smaller than those associated with scaling rainfall gauge data over space. Tandem deployment of tipping bucket rain gauges has been proposed for its many advantages (cf. Ciach and Krajewski 1999, Steiner et al. 1999, Constantinescu et al. 2006). The most important advantage is data quality control. Since rainfall shows large variability in space and time, lack of objective analyses of data quality using a single gauge’s record often prevents the detection of gauge malfunction. An added benefit of having a pair of gauges is a reduction of the random error (Ciach 2003).

By measuring surface drop size distribution (DSD), disdrometers collect additional information about rainfall processes. These data can constrain remotely sensed rainfall and enhance radar reflectivity, optical extinction, and kinetic energy budgets estimates. Extensive comparisons were made among different manufacturers of disdrometers and protocols exist to assure data quality (rf. Sheppard and Joe 1994, Campos and Zawadzki 2000, Williams et al. 2000, Tokay et al. 2001, Miriovsky et al. 2004, Tokay et al. 2005, Krajewski et al. 2006,).

Vertically pointing radars provide information necessary to interpret and constrain space-based remote sensing. These radars observe the vertical profile of precipitating clouds and identify features that directly affect weather radar-rainfall estimates. These features include, thickness and height of the melting ice in clouds (i.e., bright band problem), precipitation phase, convective cores, updrafts and downdrafts, and the vertical profile of drop size distribution—all of which aid in our understanding and ability to scale processes among time and space. Profiler based studies of precipitation systems and the related instrumental and estimation issues are well documented in a number of publications (rf. Gage et al. 1999, 2000, and 2002, Williams 2002, Williams et al. 2000, Kollias et al. 2002).

**X-band Weather Radar, Instrument Description:** An attractive emerging technology is networked inexpensive X-band weather radars. Matrosov et al. (2002) and Anagnostou et al. (2004) among others have demonstrated the advantages of using X-band polarimetric radars for rainfall estimation. Because X-band radars are widely used for navigation, many manufacturers compete in this market, making their cost competitive with good service and availability. This also reduces the cost of ancillary equipment. As compared to C-band and S-band radars, the X-band’s relatively small antennas give high azimuthal resolution. For example, to achieve 1.5° resolution requires an antenna with a diameter of ~ 2 m. This translates to a significant cost advantage compared to C- and S-band. This size antenna is also easy to install on a small building or to mount on a trailer.
The X-band polarimetric measurements also have increased sensitivity to rainfall, as compared to longer wavelengths (e.g., Matrosov et al. 1999 and 2002, Zrnic and Ryzhkov 1999). The physical concept behind polarization diversity is that, under aerodynamic forces, falling hydrometeors take oblate shapes, which depend on their size, and as a result, impact differently the propagation and backscattering of incoming horizontal (H) and vertical (V) electromagnetic waves. Knowledge of these parameters improves rainfall estimation and enables retrieval of drop size distribution (e.g., Bringi and Chandrasekar 2001, Anagnostou et al. 2004).

**Accuracy and Precision:** Accuracy and precision of these radars’ quantitative precipitation estimates remain an active subject of research. A network of such radars will be able to (1) detect and track storms; (2) distinguish areas of rainfall, hail, snowfall; (3) provide high spatial and temporal data; and (4) reduce the error level currently reported in the literature due to averaging estimates from several radars.

**Working Conditions and Environment:** These radars can be designed for unattended continuous operation over extended periods of time. They are reliable for work across a wide range of climatic conditions from arctic to tropical environments. Adjusting them to work in severe conditions (extreme heat or cold) may require special modifications.

X-band (3 cm) waves are subject to more attenuation than the longer C-band or S-band waves in heavy rainfall. This becomes important when operating it over large spatial ranges (current operational NEXRAD network provides coverage for most of the United States), but since our focus is across relatively small spatial ranges (i.e., watershed scale) and high resolution, the attenuations become insignificant. If the network radars’ coverage is limited to ~20 km², and multiple radars are used to look at the same area from different directions, the resultant multi-radar estimates of rainfall will also not be subject to large attenuation. Some radars that use polarimetric-based measurements, such as the propagation differential phase, are insensitive to partial attenuation.

**Deployment and Support:** Small X-band radars can be mounted on light trucks or flatbed trailers. Site preparation requires only firm footing for hydraulic stabilizers. Sites should have clear view in the direction of target basin (area). Electric power needs to be provided, although in some cases the radars can run powered by Diesel generators with operating duration limited only by the availability of fuel. While these radars can operate unattended, access to frequent technical support is necessary as there is little experience with such radars and networks. While a single truck-mounted has potential value, a network of ~4 radars will offer increased reliability and redundancy in data quality and assurance, and reduce in random error.

**Costs:** The cost of a network of 4 radars would be $1,000K. This cost does not include software that would generate network-based rainfall products ready for use by hydrologic scientists.

**Data Processing (QA/QC):** Data collected by the radars could be processed on site and/or transmitted to a central location wirelessly. The bandwidth of the current wireless technology permits this solution. Software that would operate the network in concert is not
available. Data processing and product generation algorithms are available within the research community and would have to be adapted to operate the network. The polarimetric capabilities of the radars would facilitate non-rainfall echo detection as the polarimetric signatures of ground clutter, insects, solid precipitation, and liquid precipitation are substantially different allowing for easy classification. To fully realize all of the above benefits, continual technological advancements in radar hardware, software to operate the radar as a true network and, rainfall estimation algorithms have to be made.

Where in the Diagonal (Space/Time): Rainfall products provided by the above network of X-band polarimetric radars could have spatial resolution as high as 100 m by 100 m and temporal resolution of 1 to 5-min. They could cover an area of 1000 km² and operate for periods of ~10 years.

3.2 Snow and Snow Melt

Because much of the land-covered portion of the earth is covered by seasonal snowpack, snow is an important component of the annual water cycle (Likens and Bormann 1995, Dingman 2002, Shanley et al. 2002). In the relatively arid Western United States, for example, snowmelt runoff from the mountains supplies high-quality water, via reservoirs and aqueducts, to communities and cities as well as for agriculture and forest productivity. In more humid areas, snowmelt fills reservoirs and recharges groundwater to offset summer water demand. In some areas, snow is monitored as an avalanches threat (Peterson et al. 1994, Mock and Birkeland, 2000), and as a flood hazard in the case of rapid snowmelt. Fish kills have been linked to high concentrations of acid eluted from initial melting waters (Johannessen and Henriksen 1978, Bjerkes et al. 2003). However, predicting the magnitude and timing of melt across a complex landscape is a daunting task.

Snowpacks vary greatly in texture, layering, moisture content, and duration in time. High alpine snowpacks of the West tend to be fine-crystalline “cold” snowpacks. They are devoid of layering and relatively static during the accumulation phase, except for the development of depth hoar at the pack’s base (Serreze et al. 1999, Mock and Birkeland, 2000). Snowpacks in the East and mid-West are subject to freeze-thaw cycles and rain. They may contain ice lenses, crusts, and other structural features (Shanley et al. 1995). Other research has shown that intermittent melting and refreezing leads to snow particles with a granular texture and larger, amorphous grains (Albert and Hardy 1993).

The ablation phase is commonly of most interest to managers and researchers. Snowmelt results from the interaction between the atmospheric forcing (radiation, latent heat flux, humidity) and the snowpack characteristics and status (Anderson 1968). To begin melting, the snowpack must warm to 0°C. Initial melting water infiltrates and increases snow density until the snowpack is saturated, then discharge of melting water begins (Rohde 1998).

Fundamental snow measurements are depth and snow water equivalent (SWE). SWE is the true measure of snow quantity, and together with snow depth (yielding density) gives an indication of snowpack condition. Other information on snowpack structure, including grain size, classification, and layering, is more difficult to acquire, but indicates snowpack status and metamorphosis (Albert and Hardy 1993). From a landscape perspective, the snowmelt process is extreme-
ly variable depending on elevation, aspect, slope, and canopy cover. Albedo has a strong influence on melt rate. These parameters affect both the forcing variables and the snowpack characteristics, causing spatial variation in the water delivery timing from the snowpack (Anderson 1968).

Much snow measurement work still focuses on spatial distribution of snow depth, and more importantly, SWE. This is true not only in research, but also as input for regional snowmelt runoff models, flood forecasts, and agricultural outlooks. Research applications (e.g. watershed hydrologic and biogeochemical modeling) tend to require SWE estimates at finer resolution than national scale surveys and networks provide (e.g., NOAA’s aerial gamma-radiation based mapping, SNOTEL snow pillows, Serreze et al. 1999).

Numerical modeling and the prediction of runoff from snowmelt is hindered by a lack of knowledge regarding spatial scaling data, particularly at local scales. Finer-scale application of gamma-radiation is a potential way to improve localized SWE data acquisition. LIDAR is also potentially valuable because of the high detail provided, though snow depth is the product rather than SWE.

**Airborne LiDAR Instrument Description**: LIDAR (Light Detection And Ranging) is perhaps the most valuable airborne tool for mapping snow depth. LIDAR can be used to map snow surface topography in the same way it is used to map land surface topography. Snow depth is estimated from the difference between ground returns and the returns given from the apparent surface of the snow. Other useful products obtained from LIDAR datasets include digital elevation- and vegetation maps. LIDAR can directly improve estimates of surface conditions effects (e.g., vegetation canopy) on snow accumulation and ablation.

**Accuracy and Precision**: LIDAR can achieve 0.5 m horizontal resolution and snow depth accuracy to 2-3 cm. LIDAR can identify snow drifts and ablation rings around individual trees. The resolution is better than the NOAA gamma radiation survey approach.

**Working Conditions and Environment**:

**Deployment and support requirements**: An airborne platform and supporting crew is required to map at watershed scale. Experienced technician required for the instrument.

**Costs**: Costs approach $1000K for accurate characterization of watershed during extended snow-covered season. The technology exists. However, airborne LIDAR is expensive. Synergies with commercial cooperators may make the technology more feasible.

**Data Processing (QA/QC)**:

**Where in the Diagonal**: Subwatershed spatial scales. Daily temporal sampling resolution is possible with seasonal observations being.

**Sled-mounted radar Instrument Description**: Several types of mobile radar are potentially useful for measuring snow depth and SWE. Examples include ground-penetrating radar, impulse radar, and Frequency Modulated Continuous Wave (FMCW) radar. FMCW radar has been used extensively to measure the thicknesses of snow on the Greenland ice cap, but can also be modified to measure SWE and other stratigraphic features in shallow snowpacks.
**Accuracy and Precision:** Determines SWE to +/- 10%, and depth of structural features within the pack to +/- 2%.

**Working Conditions and Environment:** FMCW radar is commonly applied in the Arctic to measure 100’s of meters of firn. However they can be applied to ~1-m snowpacks by using very high bandwidths (up to 10 GHz), which gives very high vertical resolution (~1cm).

**Deployment and Support:** Need a sled and appropriate terrain. Research level technician to support.

**Costs:** The basic component cost is ~$50K, but more money would be required to design a multisensor system to optimize measurements for different snow conditions.

**Feasibility:** The technology is at hand and is feasible for watersheds that are accessible by sled.

**Where in the Diagonal:** In the middle. The sled-mounted radar can acquire data over a broad area (e.g. watershed scale). Multiple samples could be taken over a period from weeks to months.

**Development Stage:** Sled-mounted FMCW radar is not commercially available, but currently 4 prototypes are being built by H.P. Marshall of U. Colorado for a NASA project.

**Mobile Snow Lab, Instrument Description:** Given the difficulties of snow measurements in complex terrain, and the expense of airborne measurements, highlights the utility in obtaining accurate ground-based measurements on as many discrete points as possible. The National Resources Conservation Service operates SNOTEL (SNOWpack TELEmetry) systems in the Western US (www.wcc.nrcs.usda.gov/snotel). Many published papers extrapolate from one or two measurement stations, sometimes outside the watershed, necessitating the need for relaxed assumptions on lapse rates and other important model parameters. Clustering of 12 to 20 SNOTEL-like stations in a watershed would provide a wealth of information on spatial and temporal dynamics of Snow Water Equivalent (SWE) and resolve some of the driving meteorological variables at these larger spatial scales. Measurements should include precipitation, temperature, snow depth and SWE, and net short- and longwave radiation. Sites within a basin could be linked with a wireless sensor network, possibly then using the SNOTEL meteor burst communication technology or any other convenient method to transmit data to- and from a central hub. The most critical instrument in the SNOTEL assemblage is the snow pillow, but it is also the least portable. Also, snow pillows often perform poorly in layered snowpacks, where ice lenses can distribute pressure in unpredictable ways. A potential replacement for the snow pillow is the snow sensor, a 10 to 20-m long flat band cable along which the dielectric constant at low and high frequencies is measured, to allow for determination of snow density and SWE either as an average or spatially distributed along the flat band. The snow sensor is currently under development in Switzerland and in the US (http://www.wsl.ch/staff/manfred.staehli/snowpower/summary.ehtml).

**Accuracy and Precision:** Instrument by instrument determination required.
Deployment and Support: Logically the installation would be for an entire snow season. This would limit deployment to one site per year. Depending on access times to individual stations, set-up and dismantling should each take about a week.

Costs: The standard SNOTEL station costs about $25K. All of the instruments excepting the snow sensor are in common use and could be selected from established sources. Replacement of the snow pillow with the flat-band snow sensor is not expected to increase this cost. The flat-band sensor may also eliminate the need for the acoustic snow depth sensor. However, the net-wave radiometer is not standard and would cost an additional $5K. For more detail on the energy balance, incoming and outgoing short and long-wave radiation could be measured individually for \(~\$15K\). Note that these radiation measurements have high and localized variability under forest canopy. Depending on the number of stations, cost could be kept to around $500K. Some R&D could go into finding economies of scale, and in ways to transport and deploy the mobile laboratories from watershed to watershed.

3.3 Evapotranspiration

The direct evapotranspiration (ET) measurements are of great value to basic and applied research in water balance characterization, understanding land-atmosphere interactions (IPCC 1995, Law et al. 2002), and making day-to-day water resource decisions. Because ET estimates characterize soil water depletion, they have high utility in a wide range of agronomic activities (Pereira et al. 1999, Burt et al. 2005), irrigation decisions (Allen 1995), runoff prediction (Kalf and Woolley 2005), biogeochemistry modeling; (Williams et al. 2001), and integrated surface water-groundwater modeling. Their utility crosses natural and managed ecosystems (e.g., predicting and constraining runoff; Generette et al. 2005, modeling soil water; Liu et al. 2005). ET estimates are used to parameterize atmospheric water budgets (Rasmussen 1967). Direct ET measurements have utility in energy balance studies (Loescher et al. 2005, Gholz and Clark 2002), determining biosphere processes and feedbacks (Law et al. 2002, Dickinson et al. 2003), processes controlling climate variability (Potter et al. 2002), and climate change (Dickinson et al. 2002). Even though ET can also be estimated at scales of interest using either the Penman-Monteith or Priestley-Taylor approaches (Penman 1948, Priestley and Taylor 1972, Monteith and Unsworth 1990), measurement and modeling schemes lack the ability to describe observed behavior, and fail to link interactions among different components of the hydrological cycle (Sivapalan 2005), particularly for scales larger than catchment.

Partitioning ET between pathways and identifying the ET water source is extremely difficult. Existing ET measurements are typically made at the leaf, plant, and sub-watershed scale through a variety of methods, each with their own sources of uncertainty. Depending on the scale, mass balance methods rely on either Fick’s law, or on turbulent transport, through modifications to the conservation equation and Monin-Obukhov similarity functions (Kaimal and Finnigan 1994). All methods rely on steady-state or stationarity assumptions, which cannot fully address the dynamic and spatially heterogeneous nature of ET fluxes through time and space (Kanda et al. 2004) or capture very stable atmospheric conditions. Over the past decade research has focused on identifying flows not
accounted for by measurement schemes (Lee and Hu 2002, Soler et al. 2002, Staebler and Fitzjarrald 2004, Loescher et al. 2006b) and during conditions when Monin-Obukhov similarity assumption are not valid. Challenging conditions include large, heterogeneous areas and below canopy environments (Hsieh et al. 1996, Mahrt et al. 2001).

The scientific uncertainties that persist on spatial and temporal scales are created by complexity in structure and mismatched scales of measurement. An example of mismatched measurement scales can be seen when leaf-level resistances are made on a few leaves, and ET is modeled using above canopy climate data measured a few km away. Even with virtually unlimited funds, it is difficult to measure all the spatial variability in leaf resistances within a sampling period. Differences in leaf age, species, attributes with height above ground, and changes in these differences through time, all contribute to uncertainty in spatial representative of measurements. Above-canopy temperatures, water vapor, and net radiation could very well differ from conditions that the measured leaves actually experience, particularly when attempting to model ET through time in complex orography. In another example, closed-canopy forests often have below-canopy environments that can be decoupled from above-canopy environments causing counter gradients in temperature and water vapor, making measured leaf attributes confounding, and making the recycling of latent energy and development of flows below the canopy possible. In a final example, differential heating of a plant canopy, partial cloudiness, and large sweeping and ejection motions (Shaw 1985) can skew sub-watershed scale, time-averaged wind statistics making estimates of transport unreliable. These examples speak to the complex, non-linear, deterministic, and often stochastic processes that control ET.

Improvement in temporal and spatial ET estimates across heterogeneous landscapes is possible through integrating measurements and modeling. Data assimilation techniques show promise in constraining measurements at one scale to model estimates at another scale, or optimizing model parameters through Kalman filtering with measured data (van den Boogaard and Mynett 2004). Measurement strategies will have to i) directly establish process-oriented, functional relationships between biotic and abiotic controls on ET across discrete temporal and spatial scales, ii) reduce overall uncertainty in estimates, iii) establish and maintain the long-term comparability of results among research studies and iv) have the ability to explore new approaches to extend measurements to larger scales, i.e., data assimilation approaches.

To make significant advances, there is a need for arrays of networked, low cost, low power, small wireless sensors that are deployable over larger spatial scales to better characterize the sub-catchment scale and leaf-level controls on ET. To establish process-oriented linkages however, across a range of spatial scales, instrumentation is required to make continuous, high temporal resolution measurement of ET and the mechanisms that transport water vapor from the surface. There are a number of instruments that have this ability including: i) eddy covariance tower-based systems coupled with fast-response O\textsuperscript{18}/O\textsuperscript{16} analyzer (i.e., integrated cavity output spectroscopy) that can differentiate the sources of transpired water from subsurface flows or those from deeper aquifers as well as measuring all scales of turbulent transport and the surface energy balance; ii) Sodar-RASS (Radio Acoustic Sounding System,
which measures temperature with height) that enables a link between sensible fluxes (and by difference latent heat fluxes) to transport processes in the lower fraction of the atmospheric boundary layer; iii) large aperture scintillometry: Large aperture scintillometer(s) coupled with a tunable microwave system(s) can, on a horizontal line, integrate surface energy fluxes at scales of ~10 km to access the inherent patchiness and heterogeneous nature of the surface fluxes at smaller scales, thereby linking 1-D eddy covariance measurements to scales used in the grid box size of numerical models or satellite remote sensed pixels; and iv) scanning water vapor lidar, which using repeated terrain-following scanning patterns, can quantitatively and areally measure the distribution and evolution of water vapor mixing ratio over a given canopy.

**LAS – Large Aperture Scintillometer (LAS), Instrument Description:** Surface fluxes of sensible and latent heat flux (H and \( \lambda E \), respectively) can be estimated with accuracy and precision over homogeneous areas (stand to ecosystem-level) using the eddy covariance technique. However, direct measurement of surface fluxes that are representative for larger landscapes (i.e., comparable to the grid box size of numerical models or satellite remote sensed pixels) are more difficult to obtain because of the inherent patchiness and heterogeneous nature the surface properties at these scales. Moreover, simple scaling techniques from single-point measurements to landscape scales often fail due to the nonlinear behavior in both fluxes and the surface properties.

The scintillation technique is one of the few techniques that can provide fluxes at scales of several kilometers, ~10 km. Through the combination of a near-infrared large aperture scintillometer (LAS) and a millimeter wave scintillometer (MWS), also known as the two-wavelength method and a tunable microwave package can estimate the surface fluxes of both H and \( \lambda E \) at these scales. The sole use of a LAS system allows measuring the sensible heat flux, turbulence statistics including the refractive index of fluctuations \( C_n^2 \) and the Fried parameter, and cross wind speeds. Estimates made by the LAS are line-averaged that have a Gaussian distribution.

*Working Conditions and Environment:* Best suited for measurement observatory or large infrastructure instrument

*Deployment and Support:* This system also requires a PhD level supervisor.

*Costs:* Cost: ~$185K, LAS; models BLS500, SLS 40A, and custom microwave package Scintec AG, Tübingen Germany.

**Eddy Covariance Technique (EC), Instrument Description:** Tower-based EC studies have improved our understanding of temporally- and spatially integrated energy fluxes, and identified key biotic and abiotic processes that control these rates (Loescher et al. 2005a, Jacobs et al. 2002, Law et al. 2002). EC measurements have been advantageous in the evaluation and improvement of biogeochemistry models (Thornton et al. 2002, Law et al. 2002, Williams et al. 2001), and useful in developing regional approaches to constraining the energy budget (e.g., Chávez et al. 2005, Kustas et al. 2005). Development of the EC technique has been of great value to both basic and applied research and has aided our understanding of land-atmosphere interactions (IPCC 1995). The net ecosystem exchange (NEE) is estimated between land
and atmosphere by the addition of turbulent exchange and the height-integrated rate of change (storage) of energy, Eq 1,

\[
NEE_z = \frac{w}{l} \frac{d}{dt} s' + \int_0^Z \frac{d}{dt} s' dZ
\]

where \( w \) is the vertical wind speed, \( s' \) is the trace gas concentration in question, term I is the EC, the prime denotes deviations from the mean (i.e., turbulent fluctuations), over-bar indicates a time average. Term II is the change in storage of \( s \) below the measurement height (\( z \)), and is thought to be equal to zero over a 24-hour period, but can be significant over shorter time intervals. The EC technique is very robust across all temporal scales, particularly for energy fluxes in unstable atmospheres. Fluxes not accounted for in the simplification of the continuity equation to derive Eq. 1 can occur in stable environments and in complex terrain for scalar fluxes other than energy.

**Working Conditions and Environment:** Best suited for measurement observatory or large infrastructure instrument

**Deployment and Support:** Instrumentation packages used for this technique would have to be assembled, there are no turnkey systems. Software packages are freely available. Even with strong QA/QC protocols and procedures in place, this system should not be operated unattended for more than 7 d. This system also requires a PhD level supervisor.

**Costs:** ~$110K w/ meteorological package and another ~$5K y-1 in consumables

**Integrated Cavity Output Spectroscopy (ICOS), Instrument Description:** Having the ability to measure fast response (e.g., ~10 Hz) water vapour isotopes, \( O^{18}/O^{16} \) can be used to partition the sources of evapotranspiration in real time, i.e., from free evaporation, and can differentiate transpired water from subsurface flows or from deeper aquifers. Advances in the production of inexpensive, robust communication lasers have enabled the development of a modified cavity ring-down technique that requires no calibration or standards. This instrument is very stable, can be driven, flown, or operated in a stationary environment. Measurements of \( O^{18}/O^{16} \) can be made with high precision, better than 0.5‰, and are able to dovetail with existing EC systems. Fluxes measured would be at the stand to ecosystem scale.

**Working Conditions and Environment:** Best suited for measurement observatory or large infrastructure instrument

**Deployment and Support:** This system also requires a PhD level supervisor.

**Costs:** ~$55K, Water-vapor isotope analyzer, Los Gatos Inc. Mountain View, CA http://www.lgrinc.com/index.asp

**SODAR-RASS, Instrument Description:** A SODAR-RASS (Sound Detection And Ranging – Radio/Acoustic Sounding System) is an active sounding system that uses acoustic and radiomagnetic waves to sound the lower fraction of the atmospheric boundary layer (ABL). This is achieved by emitting sound pulse and tracking as it vertically propagates through the ABL to measure the speed of sound and thus to derive acoustic temperature profiles and structure (\( C_T \)) within a vertical column of boundary layer space above the sensor. The received backscatter (reflectance) of the emitted acoustic waves is also used to
derive detailed, mean 3-d vectors for the flow (wind vector), wind directions, turbulence parameters and acoustic backscatter intensity. Vertical sensible heat fluxes can be estimated with high precision once the system had been scaled with a sonic anemometer. Sodar-Rass data used in conjunction with measurements made at common observational towers can constrain the atmospheric processes that control the exchange of energy. Typical maximum height ranges extent as far as 1000 m above ground. However, actual heights may vary with proximity to sound sources and weather conditions (e.g. precipitation, very strong winds). Typical sounding frequencies of the Sodar are within the audible range of 1 to 3 kHz., and the radiomagnetic frequencies used for the RASS are within the range of 1 –3 GHz.

**Working Conditions and Environment:** Best suited for measurement observatory or large infrastructure instrument.

**Deployment and Support:** An advantage of a Sodar-Rass is its mobility, easy setup, user-selectable height resolution and sounding frequencies. Advantages include that this technology is appropriate for use in natural and urban environments. This system also requires a PhD level supervisor.

**Costs:** ~$285K, Multifrequency SODAR with PC for operation, controls and analysis, RASS- extension (Model METEK Phased Array DSDPA.90-24).

**Ground based LIDAR, Instrument Description:** The magnitude of ET depends to a large extent on soil water processes within the soil profile. On the other hand, by knowing the ET across the landscape, conclusions about the spatial distribution of soil functional properties and soil water processes within the soil profile and the vadose zone can be drawn. Therefore, the spatial pattern of ET across a section of the landscape as a function of time would add to our current knowledge on soil mapping and land classification as it contributes to an understanding of dynamic processes without being based on static soil variables.

Under “wet” soil surface conditions, the spatial variability of the rate of ET is generally minimal inasmuch as ET is controlled by local atmospheric conditions. Spatial differences in ET become more pronounced with decreasing soil water content. Evaporation from the soil surface depends markedly on the water content at the land surface, while water absorption by plant roots and subsequent transpiration from plant surfaces can be reduced when water in the soil profile decreases. In addition to land surface topography and soil texture, land use and management also contribute to spatial differences of soil water balance. Areas covered with a highly productive deep-rooted agricultural crop may transpire more water on a particular day than areas with more extensive, shallow-rooted crops. On the other hand, with the same crop being grown across an entire field, transpiration may differ spatially with lower rates prevailing in zones long before wilting phenomena can be identified. Knowing the spatial pattern of ET across the landscape is expected to significantly add to our knowledge of spatio-temporal soil processes in the landscape. The measurement of ET and its resolution in space and time should coincide with measurements of the soil water content at the land surface (see below Soil Moisture Measurement using Ground Based Microwave Methods). Existing field meteorological
or weather stations provide data for a point measurement of ET. To our knowledge, the only tool that provides the aerial distribution of ET within relatively short time intervals is the LIDAR technique.

LIDAR stands for Light Detection And Ranging. A LIDAR instrument emits and receives electromagnetic radiation at a higher frequency than that of a radar instrument. The emitter is a laser, and its receiver is an optical telescope. With different LIDAR techniques, different constituents of the atmosphere can be quantified, e.g., water vapor, carbon dioxide, ozone as well as aerosols etc. Water vapor LIDARs (see also Section 5.1.b), which typically provide remotely sensed water vapor mixing ratio at specified range gates and over a specified range, can contribute significantly to the science at scales outside the research envelope shown in Figure 1. Current water vapor measurement techniques using lasers can be classified by technique in two categories: 1) Raman (WVR) and 2) DIAL (Differential Absorption LIDAR, WVD).

Using a tunable laser, WVDs operate by measuring the difference in absorption of two transmitted optical signals (at a given range), one at a wavelength that is readily absorbed by water vapor molecules and the other at a wavelength that is not. This measurement is then converted into a measurement of mixing ratio (generally reported as g kg$^{-1}$), taking into account errors introduced by aerosol, temperature gradients and other effects. The range of WVD is determined by the attenuation of the signal and so the expected mixing ratios should be considered in the design of such systems. The pioneering work in this area, particularly from aircraft, was by Browell of NASA (Browell et al. 1979) and also by Ehret of DLR Germany (Ehret et al., 1993).

WVRs determine the mixing ratio of water vapor by measuring the relative intensity of Raman backscatter from water vapor and nitrogen (Goldsmith 1998, Whiteman, 2003a, b). These systems have more limited range or require long averaging times due to the weak Raman signal, but their measurements are less adversely affected by attenuation or aerosol which allows for more convenient lower tropospheric operation than WVDs. WVRs need to be calibrated against a reference measurement of mixing ratio (typically an atmospheric radiosonde). Their inherent accuracy, with good calibration is approximately 6% (quite system dependent). WVRs, depending on the wavelength used, may only be able to measure accurately at night or during the day. Different research groups have been active in the development of WVR for monitoring water vapor, e.g., the Johns Hopkins University (JHU) and Los Alamos National Laboratory research groups. Applications of this scanner are published in Eichinger et al. (2000, 2006) and Cooper et al. (2003). One of the few devices that may become commercially available during the next year is built by LEOSPHERE, France. The technical capabilities of these WVR are similar for both the systems (JHU group and LEOSPHERE).

Accuracy and Precision: The specifications of currently available systems vary depending on range gate size and averaging time, although published accuracies of water vapor mixing ratio fall in the range of 5-10% or at least 0.1 g kg$^{-1}$ (Wulfmeyer and Walther 2001a, b). The dynamic range of the NASA WVD (known as LASE), for example, is 0.01 – 20.00 g kg$^{-1}$. WVD systems measure water vapor only, while WVR systems also can also be configured to measure cloud water/droplet radius, aerosol properties, and optical properties of clouds. For WVR, Cooper et al. (2003) gave
an absolute accuracy for water vapor measurements being ± 0.34 g kg\(^{-1}\) at the 95 % confidence level. Intercomparisons of measurements by these two techniques have been undertaken at the DOE ARM CART site and novel uses of these systems have been explored during the International H2O Experiment (IHOP, Weckwerth and Parsons et al. 2006).

**Working Conditions and Environment:** Important elements for the operation of WVR and WVD LIDAR are 1) eye safety, 2) mobility or transportability and 3) day/night operation capability. For systems that do not operate in very eye-safe wavelengths (e.g. in or near the visible spectrum), power and/or beam width (e.g. high-repetition rate micro-pulse systems) must be reduced sufficiently, which sacrifices range and resolution. Field deployable water vapor LIDAR (RAMAN) has been used successfully above bare soil, and short and tall vegetation (grass to trees). The system can work across a range of different environmental conditions, i.e., the LEOSPHERE system operates at temperatures between -10 and 45 °C and between 0 and 100 % relative humidity.

**Deployment and Support:** The system can be used from many different platforms, such as airplanes, trucks, and stationary. For the studies suggested here, placement on a vehicle or a stationary platform at the corner of a field is most suitable. Measurements should be taken several times a day to observe the temporal change of spatial patterns of ET. A well-trained technician is necessary to manage the system to perform measurements.

**Costs:** Depending on the scanning, range, and range gates required by the scientific goal, hardware costs can vary from $100K to $1,000K for a new water vapor lidar. Fabrication and software engineering is also highly variable depending on the level of finish and automation desired. Costs for LIDAR scanner developed by the JHU/LANL groups are not available yet. The price for the LEOSPHERE system is $138K to $175K (110K to 140K EU).

**Data Processing (QA/QC):** For data processing a WINDOWS XP interface exists. A system working under LINUX is in development for the LEOSPHERE scanner. Algorithms for data analysis exist for the LEOSPHERE system.

**Where in the Diagonal (Space/Time):** The water vapor LIDAR scanner is expected to reflect spatial and temporal changes of soil water transmission properties across the landscape. This instrument will be able to provide a better understanding of water fluxes and evapotranspiration at the field scale and over relatively short time scales in the order of one day, i.e., at a combination of space-time scales illustrated in Fig. 3 that could not be previously explored by soil scientists. At this space-time-scale combination, we anticipate not only a significant contribution to functional soil characterization for validation or refinement of existing soil classification, but also a better approach to local soil-water balances. Usually, the evapotranspiration part of the soil water balance is based on a measurement of agroclimatological variables at a single location, often not even located at the experimental site but at a considerable distance away. The calculated evapotranspiration is assumed to be spatially homogeneous.

The benefit of an instantaneous measurement of the spatial variability of evapotrans-
piration across a field or a landscape crossing different landscape, land use, and soil management units is based on the fact, that evapotranspiration does not have to be assumed spatially homogeneous anymore. The invalidity of this assumption has been shown in pilot applications of a WVR LIDAR scanner where areas with different vegetation contributed differently to the water vapor concentration in the atmosphere (Eichinger et al., 2000). Even earlier, Eichinger et al. (1993) found that evapotranspiration differed considerably in different zones of an alfalfa field, even though the field had been managed homogeneously.

3.4 Hillslope Processes and Stream Flow Generation

Processes that give rise to streamflow generation (i.e., the delivery of water from the terrestrial and near-stream system to the stream channel network) develop from a myriad of complex behaviors at spatial scales from plots, hillslopes, catchments, to watersheds. A variety of environmental problems and ecosystem functions require an understanding streamflow generation processes. Streamflow processes control ecological and biogeochemical processes, exchange reactions, and mineral weathering rates. For example, stream nutrient dynamics are often very sensitive to lateral flow paths through shallow organic soils. These zones become “activated” during storm events and water frequently mobilizes or flushes labile constituents (e.g., Hornberger et al. 1994). Over longer timescales, flow paths determine the geochemical evolution of water resulting from subsurface contact duration (or residence time). This duration partly controls on the stream water chemistry (Burns et al. 2003). Streamflow generation processes also are important for extreme events and flooding. Overland flow (e.g., from impervious surfaces) is a rapid pathway. Saturated areas expand and enhance the hydrograph response. The combination is manifested in downstream flooding.

The major streamflow generation processes have a straightforward description. However, their complex spatial and temporal pattern is difficult to elucidate and results in a unique signature for each watershed (Beven 2000). Streamflow generation processes can be functionally described as quickflow and delayed flow. Quickflow results from surface (e.g., overland flow) and subsurface flow processes. Delayed flow is primarily from subsurface processes (e.g., streamflow contributions from aquifers). Overland flow is rarely observed in undisturbed upland watersheds; thus, streamflow generation processes are largely composed of rapid subsurface flow and saturation-excess sources.

Subsurface flow processes are often considerably slower, more tortuous and more difficult to distinguish than surface flow processes. Subsurface flow is broadly separated into shallow and deep processes. Deep subsurface flow is the groundwater flow component, which contributes to the baseflow. Shallow subsurface flow is the lateral flow of water through permeable shallow soils. Perched water tables above soil with lower permeability are a common source of shallow subsurface flow. Shallow subsurface flow also results from unsaturated flow (Harr 1977), pressure-waves (Torres et al. 1998), and macropore flow (Beven and Germann 1982). Shallow subsurface flow processes have perplexed hydrologists since the early work of Hursh (1936, 1944) and are often ignored. The challenge is to explain how subsurface flow causes such a rapid streamflow response when measured soil matrix hydraulic conduc-
tivity data predict much lower soil water velocities. The recent advent of environmental tracers (e.g., C1−, 18O, 2H) allow hydrologists to characterize the stream water composition (Sklash et al. 1976, Pilgrim et al. 1979, Buttle 1994). Long-term, high resolution tracer data are being used to estimate the travel time distribution of all water contributing to streamflow generation (quick and delayed flow) (Kirchner et al. 2000).

Stable isotopes of water (e.g., 18O and 2H) are a recent addition to the standard toolkit to study flow pathways, residence times, recharge sources, and water mixing. Stable isotopes are ideal tracers of hydrological processes because they are naturally part of the water molecule. The isotopic composition of water changes only through mixing and well-known fractionation processes that occur during phase changes. Unlike applied tracers, stable isotopes are environmental tracers that are added naturally at the watershed scale by rain and snowmelt events. This addition conveniently provides water tracers to identify water sources and water transport (Broad 2005). Isotope hydrology has grown in recent years from less than 100 papers published between 1960-1965 to more than 7000 published between 1995-2000 (Aggarwal 2002).

Until now, the analytical expense of processing samples using an isotope ratio mass spectrometer (IRMS) and the lack of field deployable devices forced hydrologists to collect limited datasets. Recently studies show that limited temporal resolution datasets mask interpretations and misrepresent fundamental hydrologic processes (e.g., water travel times, Kircher et al. 2004). Streamflow flowpaths have travel times that range from hours to decades and must be sampled at timescales appropriate to characterize the fine timescales of events (i.e., hours) as well as the timescale of baseflow generation (weeks to years). The isotopic composition of other components of the hydrologic cycle such as transpired water, open water evaporation, evaporation from canopies, and soil and ground water will allow for better characterization of processes and relative storage capacities of water cycle components. Stable isotope measurements have the potential to change what we know about hydrology and have already led to major advances in our science (e.g., Sklash and Farvolden, 1979).

**Water Mixing, Residence Time, and Flow Pathway Monitoring using Laser Absorption Stable Isotope Mass Spectroscopy, Instrument Description:** New technology using laser absorption spectroscopy is currently being tested for the measurement of real-time stable isotope composition of liquid and vapor water (Gupta et al. 2005). Conventional laser absorption spectroscopy uses an expensive laser light source (e.g., lead-salt or quantum-cascade) that operates in the infrared region where absorption is strong. The diode laser is tuned to a particular narrow emission wave band by controlling the temperature and current applied to the laser. The source wavelength is selected to match the absorption of a particular water isotope (e.g, H218O) and from repeated scans of the laser emission, a measured absorption spectra is recorded. The measured spectra combined with measured gas temperature and pressure in the sample chamber, effective path length (typically <200 meters), and known line strength are used to determine a quantitative measurement of isotopic mixing ratio directly and without external calibration (Kerstel et al. 1999). The addition of off-axis integrated cavity output spectroscopy (ICOS) for the la-
ser mass spectrometer (Paul et al. 2001), effectively traps the laser photons so that they make thousands of passes on average before leaving the sample chamber. Using high-reflectivity mirrors, the optical path length effectively increases to several thousands of meters and thus the measured absorption of light after it passes through the sample chamber is significantly enhanced improving isotopic determination of $^{18}\text{O}/^{16}\text{O}$, $^2\text{H}/\text{H}$, and $^{17}\text{O}/^{16}\text{O}$ (Gupta et al. 2005).

Laser absorption spectrometers have advantages over the IRMS such as smaller sample sizes, direct measurement of isotope ratios in the water vapor (avoiding the time-consuming and inaccurate sample preparations), and possibility to accurately measure the $^{17}\text{O}/^{16}\text{O}$ ratio in water (in addition to the $^{18}\text{O}/^{16}\text{O}$ and $^2\text{H}/\text{H}$ ratios) (Kerstel et al. 1999). Coupling a laser absorption mass spectrometer for water isotopes with a laser absorption mass spectrometer for carbon isotopes will allow for real-time respiration and transpiration rates to be estimated helping us understand the interaction between water and carbon cycles.

**Accuracy and Precision:** Tunable diode laser mass spectrometers determines $^{18}\text{O}/^{16}\text{O}$, $^2\text{H}/\text{H}$, and $^{17}\text{O}/^{16}\text{O}$ to better than 0.3 per mil, 0.5 per mil, and 2 per mil, respectively, with the possibility of being field deployable (Gupta et al. 2005).

**Working Conditions and Environment:** The analyzer provides continuous monitoring of either ambient water vapor (without pre-concentration) or repeatedly injected liquid samples with an autoinjector system and control software. The instrument can include a computer and internal datalogger for stand-alone operation and for controlling the water injection cycle (e.g., inject, flush with dry gas, re-inject) (Los Gatos, Inc.). Ambient temperature ranges for field operation are from 4-45 °C.

**Deployment and Support:** Methods are currently being developed to render laser absorption spectroscopy for the field. Los Gatos Research, Inc. is one such group testing the laser mass spectrometers for field use. Once this device is field deployable, it can be collocated with stream gauging stations for continuous measurement of water isotopic composition. Given continuous precipitation measurements (i.e., outfitting rain gauges with the device), the input and output compositions will allow for better hydrograph separations and residence time estimations (see McGuire and McDonnell, in press). Modifying the device to sample other components of the hydrologic cycle such as vegetation canopy water, transpired water, and soil and ground waters will allow for better characterization of processes and relative storage capacities of water cycle components.

**Costs:** At a cost of about $40,000, multiple field deployable laser mass spectrometers could be located in a watershed.

**Data Processing (QA/QC):** No calibration or drift correction is needed.

**Where in the Diagonal (Space/Time):** This instrument fits well across temporal scales (<hour, day, weeks, years) and, depending the number deployed, it can encompass spatial scales of outflow water from plot or hillslope to sub-catchment or watershed. Vapor sampling is likely to be limited to point scales with a footprint that varies similarly to eddy flux measurements. Once field deployable, it
would provide time series of isotopic composition (i.e., \(\text{^{18}O/^{16}O}\), \(\text{^2H/H}\), and \(\text{^{17}O/^{16}O}\)) for characterization of water sources, evaporation effect, mixing, and travel time.

3.5 Streamflow

At the most fundamental level, surface-water observations are measurements of water depth, width, and velocity. These measurements are used to compute flow rates, cumulative yields, travel times, and residence times. They support mapping of stream, lake, and estuary bathymetry and velocity distributions. Surface-water measurements are necessary not only for understanding watershed runoff and water yields, but they are essential for understanding the physical environment controlling geochemical and ecological processes as well. The measurements and maps characterize chemical constituents and sediment transported. They also identify habitat for aquatic flora and fauna. Recent developments in hydroacoustics, radar, and particle image velocimetry (PIV) systems, offer significant opportunities to improve surface-water measurements. The measurements would vastly expand research in watershed science. These instruments, their use, limitations, and potential enhancement, and related research opportunities are discussed below.

**Acoustic Doppler Current Profiler (ADCP), Instrument Description:** The most significant development in surface-water measurement over the last 2 decades is the development and continual improvement of the Acoustic Doppler Current Profilers (ADCPs). The ADCP measures near-instantaneous velocity and depth through the water column and can be used to map streamflow velocities and channel bathymetry (Dinehart and Burau 2003). ADCPs utilize acoustic energy and the Doppler principal to measure water velocity by comparing the frequency of an emitted acoustic signal to the frequency of the signals reflected off of materials suspended in, and moving with, the water (Simpson and Olman 1992). Time-of-flight techniques permit measurement of distances to acoustic reflectors, including channel beds and, coupled with frequency-shift information, permits profiling of multi-dimensional velocity fields through and across portions of streams, lakes, and estuaries. ADCPs are available in a diverse array of physical configurations and processing algorithms. Appropriate selection depends on the data-collection effort’s goal, the channel characteristics (depth, width, bottom material composition), and the flow (relative vertical and spatial distribution and overall magnitude of velocities.)

**Accuracy and Precision:** For most circumstances however, and in the hands of a well-trained, experienced user, the ADCP will yield results that are within 5% of the true discharge (Morlock 1994). The ADCP accuracy and precision depends on the stream channel physical characteristics (primarily depth), the uniformity of water velocities (relative to turbulence), and the signal transmission frequency, as well as the platform’s (boat) stability and maneuverability. ADCPs have limited ability to sense velocities at locations closer than 50 cm from the transducers and they are unable to distinguish velocity readings from side-lobe interference within 1 “bin” of the channel bottom. The velocities of these portions of the stream section are estimated by extrapolation of the measured velocity based on an assumed velocity profile.

**Data Processing (QA/QC):** ADCP software is available to provide a range of processing
control. Typically they depict velocity profiles in real-time and computations of velocity, depth, and instrument location as an ADCP transits the stream. Various process settings control the depth of sensed acoustic returns and the size of vertical bins into which the velocity measurements are grouped and averaged. These settings often involve trade-offs in which improved performance or better resolution for some discharge components is obtained at the expense of reduced accuracy in other components. Once data are recorded, software is available to review data, alter measurement settings, identify those factors affecting velocity extrapolations, and optimize the data acquisition to enhance the data quality. Most ADCPs however, require a separate computer to establish settings, initiate and conclude measurements, and download data.

**Working Conditions:** The ADCP is typically a rugged, environmentally sealed instrument, well suited for field conditions in which they are used. The ADCP is deployed from a variety of small boats and tethered craft. The transducer head must be submerged in water, and during floods water velocities are often high (more than 7 feet per second). Collision with suspended debris can break tether lines and destroy tethered craft and causing the ADCPs being lost. An important complication arises during floods. The ADCP utilizes Doppler shifts of acoustic signals from the channel bottom to determine its position and speed, relative to its starting position, on the stream. If the streambed becomes mobile as a result of high velocity flows, the ADCP should be integrated with a Global Position System (GPS).

**Deployment Requirements:** Deployment requirements are not extensive, but the speed and cost of deployment using manned boats depend on the size, condition, and readiness of the boat. Tethered ADCPs deployments require a secure bridge or cable. An ADCP can be set up with a minimum of time, perhaps 20-min.

**Costs:** Costs for a single unit approach $25K. A significant supplier base exists for ADCP (Teledyne RDI, SonTek/YSI, etc.) Additional costs are incurred for its deployment via onboard moving boats, small (1-2 m) boats, booms, and surf boards. Remote controlled and autonomous vehicles are being developed and are nearing availability to the user community.

**Feasibility:** The ADCPs’ power and utility are widely documented (Simpson 2001). They are an essential tool of the U.S. Geological Survey (USGS) streamgaging program. ADCPs are effective for waters of 1 m or deeper. Recent advances, suggest ADCPs will be effective in headwater streams of depths greater than 0.3 m.

**Acoustic Velocity Meter (AVM), Instrument Description:** AVMs are used to collect near-continuous velocity observations, often over lengthy periods (months), from a static mount by scanning across a channel or upward from the channel bottom (Laenen 1985, Morlock et al. 2001). Due to the limited AVM beam transmission distance, AVMs are generally used to monitor only a portion of the stream, referred to as an index section. The velocity of that section is related empirically to the average velocity of the complete cross-section (often obtained in conjunction with an ADCP).
Accuracy and Precision: Streamflow records computed by AVM-index techniques on a stable stream are generally within 5% of the actual discharge. Accuracy is diminished by the presence of stratified water of varying densities (due to differences in temperatures or salinity) which can create bi-directional flow where water at different depths is flowing both up and downstream at the same time. The accuracy and precision of discharge records depend on the stream channel configuration, the correlation between the monitored index velocity and the cross-section mean velocity, and the stream channel stability.

Data Processing (QA/QC): AVM discharge is computed from a stage-area relation or an index-velocity versus the overall average streamflow velocity relation (velocity-velocity). Stream stage (or water level) data are collected using stilling wells and pressure transducers. Stage data are applied to the stage-area relation to yield a channel-area time-series. The index-velocity records are applied to the velocity-velocity relation to create a stream-averaged velocity time-series. The two series are multiplied by one another to yield a discharge record.

Working Condition: For large streams, AVMs are often attached to driven piers just off shore. In small streams, they may be placed mid-stream on bridge piers. As the flow nearest the piers is often excessively turbulent, nearby velocities are usually “blanked” or ignored, and only those velocities further from the AVM transducer are recorded.

Deployment and Support: Deploying an AVM usually requires a boat, and potentially, barges and cranes typical of shallow water construction. AVMs do not require extensive support staff, but users should be well-trained in their use and analysis of the data they yield.

Costs: AVMs typically cost $9 to $15K per instrument. There are a small number of vendors who supply the AVM market. As AVMs are subject to considerable hazard, backup systems are needed. Supporting infrastructure (piers, shelters) can also increase implementation costs higher than the instrumentation costs.

Feasibility: AVMs are often the only viable option for gaging streamflow of critically important coastal rivers and estuaries influenced by tides and backwater. AVMs are used at 6-8% of all USGS streamgaging stations. Their use is limited to locations where persistence in velocity distributions is normal.

Where in the Diagonal (Space/Time): AVMs are frequently deployed in clustered units in lakes and estuaries. Frequent occurrence of variable inflows (downstream of locks, dam and diversion outlets) often require the installation of multiple AVMs.

Radars, Instrument Description: In-situ measurements of streamflow expose equipment and personnel to potentially hazardous conditions, especially during floods when the data may be of greatest value. Radars provide an alternative to in-situ measurements (Costa et al. 2000; Teague et al. 2001, Mason et al. 2002, Cheng et al. 2004, Teague et al. 2005, Spain et al. 2005). Surface velocity can be measured at various points across the river, using pulsed or continuous-wave side-looking radars established on the stream bank or downward looking radars mounted on a bridge. Pulsed radars permit measurement of the entire surface transect from a
single bank-side location. Continuous radar requires multiple instruments or a means to move the radar across the stream (Cheng et al. 2004). Flow measurements additionally require channel geometry (depth, width) which is more difficult to obtain than surface velocity (Mason et al. 2002).

The typical radar configuration consists of either a pulsed-wave or continuous wave microwave radar and a ground-penetrating radar (GPR) system (Costa et al. 2002). The microwave wave systems monitor surface-velocity with the GPR is used to obtain cross-sectional geometry. Pulsed radars have operated successfully at X-band or UHF radars emitting at 350 MHz. Transmitting antennas for the radar consist of 12-inch parabolic disks or Yagi antennas. Simpler and less expensive continuous wave radars, operating at 24 GHz, have also been successfully applied (Costa, written communication.) The GPR system is usually a shielded 100 mHz center frequency system mounted on a cable of bridge and suspended across the stream.

**Accuracy and Precision:** The application of radar to streamflow measurements remains an experimental process, but radar measurements of surface velocities generally confirm in-situ measurements to within 0.25 feet/second. A combined GPR and microwave configuration have yielded flow measurements with 1-percent of those made using conventional, mechanical current meters. Specific accuracies will likely depend on the stability of stream channel and wind.

**Working Conditions and Environment:** Radar systems are exposed to the same work conditions as conventional streamflow measurement systems. It is not clear how radar systems will perform during sustained exposure to rain and winds. Under adverse conditions, radar systems have provided flow and velocity data that compare well with that obtained from side-looking ADVMs.

**Deployment and Support:** There are two approaches to measure surface currents using radar. One is to employ a bank-mounted system that sweeps across the river surface measuring velocity in several “bins” or subsections. Bank-mounted surface-velocity radar systems have been mounted on simple masts, bridges, and buildings and require not special hardware or transport. The GPR systems, however, require cableways, bridges, or tall towers which may be expensive to deploy.

**Costs:** Reliable figures for the costs of the radar systems are not yet available. The pulsed wave systems are not sold routinely. Continuous-wave systems are available for about $10-15k each.

**Data Processing (QA/QC):** Streamflow velocity-measurement radars rely on Bragg scatter principals in which radar signals are reflected off of small wavelets moving toward or away from the radar antenna. The reflected signals are shifted in frequency. Plotting the Doppler spectrum typically shows two peaks (resulting from waves moving toward and away). The difference in frequencies between these two peaks is an indication of the velocity of the water surface. Detection of the peaks and associated frequency shifts can be automated (Costa et al. 2000).

**Where in the Diagonal (Space/Time):** Depending on their reliability and accuracy, radar systems could be used for either short-term flood measurements or long-term monitoring of streamflows.
3.6 The Vadose Zone

Acknowledging the variability of soil and the vadose zone in space (Stockton and Warrick 1971, Nielsen et al. 1973), and that of its transport-determining state variables in space and time (Cahill et al. 1999), precludes the simplifying assumption of homogeneous geometry that underlies many attempts to describe water transport in soils across different scales (Anderson et al. 1987). Earth scientists with increasing concerns about environmental pollution now recognize that soils, and soil landscapes, have to be characterized hydraulically at finer scales (Narasimhan 1998), and variability structure of flow and transport has to be determined at the respective scale of investigation (Russo and Bresler 1981).

Soil moisture is the natural state variable of the land surface. Its temporal and spatial variability over catchment areas affects surface and subsurface runoff, modulates evaporation and transpiration, determines the extent of groundwater recharge, and initiates or sustains feedback between the land surface and the atmosphere. At a particular point in time soil moisture content is influenced by: (1) the precipitation history, (2) the texture of the soil, which determines the water-holding capacity, (3) the slope of the land surface, which affects runoff and infiltration, and (4) the vegetation and land cover, which influences evapotranspiration and deep percolation. In other terms, the partitioning of soil moisture to recharge the groundwater, evapotranspiration to the atmosphere, and surface/subsurface runoff to the streams at different spatio-temporal scales and under different hydro-climatic conditions pose one of the predominant challenges in quantifying water cycle variability.

Vadose Zone Mobile Laboratory Instrument Description: Following the concept of Vadose Zone Research Park (VZRP) Geosciences Research Mobile Laboratory of Idaho National Lab (INL), a CUAHSI-HMF Vadose Zone mobile lab can be developed. This facility will provide a single comprehensive platform for characterizing and monitoring shallow subsurface across field environments. The facility will include a drill rig that can penetrate into deep vadose zone (e.g., ~20 m) and extract soil cores for determining soil physical (texture, bulk density, soil water retention, saturated and unsaturated hydraulic conductivity), thermal (heat capacity, thermal conductivity), and chemical (soil organic carbon, pH, SAR, EC) properties. The mobile facility will carry the necessary somewhat-automated instruments (e.g., constant head permeameters, tempe cells, pressure plates, pumps, cores/cells, disc infiltrometers, deionized water supply system, refrigeration, and fume hood), and work-bench for sample preparation, calibration, storage, and experiments. Additionally, this facility will have an advanced vadose zone flux meter installation kit for shallow ground water recharge measurements, a suite of soil moisture and pressure sensors such as time domain reflectrometry (TDRs), capacitance probes, tensiometers, wireless data loggers, multiplexing units, GPS, GIS databases, computers, and software. The mobile lab can be outfitted with other geophysical and electromagnetic tools (e.g., EMs, GPRs) for subsurface characterization, and roof-top weather/environmental measuring facilities (e.g., radiation, precipitation, wind speed, relative humidity, leaf area index) for co-located sampling of boundary-layer, surface, and subsurface water.

Accuracy and Precision: The facility will primarily take numerous point scale measure-
ments from the surface to the deep vadose zone (e.g., ~20 m).

**Working Conditions and Environment:** The instrumentation is broadly applicable to many field environments including extreme cold, hot, dust, and dirt.

**Deployment and Support:** The mobile lab can deploy site characterization and monitoring tools/devices on demand at strategic locations. A full-time technician is necessary for maintenance, operation, and trouble shooting of this facility.

**Costs:** Planning, purchasing, and fully outfitting the facility is estimated to be $250K and will take up to six months.

**Ground Based Microwave Methods, Instrument Description:** Active and passive microwave remote sensors (RS) can monitor soil moisture in large land areas (i.e., 100 m² to 1000 km²) encompassing various soil types (e.g., texture), topographic features (e.g., slope), vegetation/land cover, and climatic conditions. These remotely sensed signals give average values over an area usually known as a footprint. The physics of microwave remote sensing at L band frequencies for measuring soil moisture has continually evolved during the past 25 years. While air- and space-borne sensors are ideal for regional/global spatial coverage and for addressing spatial heterogeneity, ground-based mobile (e.g., truck-mounted) microwave instruments are cost-effective and suitable for deployment in watersheds where finer resolution soil moisture data are critical for water balance studies.

While most of these ground-based microwaves operate on a passive mode with both vertical and horizontal (dual) polarization, ComRAD (NASA-GSFC) utilizes both active (radar) and passive (radiometer) mode. Besides L-Band (0.5 cm penetration depth), C-Band passive microwave radiometers have been designed for measuring surface skin wetness (0-2 cm). Most of these ground/airborne passive microwave sensors work from several MHz to several GHz frequency range with varying incidence and azimuth angle and V/H polarization. The final product of the radiometer is a time-referenced series of data consisting of the set of beam position based on brightness temperatures. Soil moisture values are retrieved from the measured brightness temperature values.

**Accuracy and Precision:** In most circumstances the penetration depths are between 0.5 cm. The sensitivity/precision of these systems in terms of brightness temperature are typically 0-3 Kelvin. Based on the deployment height and scan/incidence angle (truck or UAV), the footprint size can vary from several square meters to several hundred square meters.

**Working Conditions and Environment:** Passive and active microwave instrumentation work best with low vegetation ground cover. Although some recent efforts show the potential for adoption in high vegetation (forested) areas no confirmatory studies are available so far. Passive systems are less prone to other extraneous signal interference than active systems. Passive systems are reliable to work across a range of climatic conditions from arctic to tropic environment.

**Deployment and Support:** Various deployment platforms (mobile truck, UAV, tower) are used for passive/active microwave sensors. Mobile microwave systems can easily be deployed across any watershed, region, or the nation as
per the demand. UAV deployments are better than ground vehicles to access and cover the entire domain. A full-time technician familiar with the system is necessary for deployment, QA/QC, operation, and trouble shooting on a regular basis. It can be acquired by the HMF community within 6 months.

*Costs:* Most of these passive microwave instruments are assembled by the PIs after acquiring various components including network analyzer, radiometer/radar antennas, deployment platform, and etc. ComRAD (active/passive microwave sensor) would cost approximately $250K for parts and labor. In addition a truck deployment platform with telescopic booms and rotors would cost $250K. Assistance is available to design these platforms.

*Data Processing (QA/QC):* Data processing algorithms for passive microwave sensors have been developed in a research mode. Most of these sensors need calibration and validation with ground based soil moisture data and standard references, and demand correction for specific soil, vegetation, topography, and temperature conditions.

*Where in the Diagonal (Space/Time):* This instrument has a range of spatial (field, watershed, and regional) and temporal scales (day, month, and year). It is designed to provide multiple measurements/time series of brightness temperature data which can reflect the soil moisture as it changes over time.

### 3.7 Groundwater

Groundwater represents the largest store of freshwater resources within the terrestrial hydrologic cycle. The National Research Council (2000, 2004) has highlighted that approximately 130 million residents in the United States depend on groundwater resources for water supply (i.e., 40% of the public water supply). Groundwater also provides a significant fraction of our national irrigation and industrial water supplies. Groundwater flows have time scales that range from monthly to decadal and spatial scales ranging 10 m2 to 100 km2. Recent reviews of research needs (National Research Council 2000, 2001, Miller and Gray 2002, National Research Council 2004) highlight the need to advance our understanding of groundwater fluxes to improve water supply management for conjunctive use of groundwater and surface water, to elucidate the impacts of climate change/variability on groundwater recharge and discharge dynamics, and to characterize water quality dynamics particularly in the context of groundwater—surface water interactions (Sophocleous 2002).

Advancing our understanding of groundwater hydrology will require local to regional scale observations of flow-and-transport processes (National Research Council 2000). Several research challenges must be addressed to permit groundwater hydrologists to move beyond traditional models of single-phase groundwater flow (Miller and Gray 2002). Preeminent is the need to better understand the “structure” of groundwater systems. The spatial structure (i.e., heterogeneity and anisotropy) of the soils, sediments, and rocks defining porous media is currently the largest source of uncertainty in groundwater recharge, storage, and flow projections. Even in relatively homogeneous sand and gravel deposits, the hydraulic conductivity is highly uncertain (de Marsily 1986). Groundwater hydrology lacks mature methods for jointly characterizing and modeling complex structures (e.g., karst terrain, fractures, faults, deep
vegetation root zones, etc).

Transport mechanisms exacerbate the challenges posed by characterizing groundwater systems as they require a highly resolved velocity field to predict chemical advection, dispersion, and reaction. Limitations in our ability to predict transport are largely due to the extremely large range of scales active in these processes (molecular to kilometer, picoseconds to decades, Dagan 1989, Miller and Gray 2002). In the context of water cycle dynamics, groundwater flow-and-transport projections are used primarily to determine the spatio-temporal distribution of groundwater recharge (inputs to groundwater systems) and discharge (outputs from groundwater systems via springs, outcrops, stream-aquifer interactions, cf. Scanlon et al. 2002).

Experimental approaches are currently being employed to study groundwater recharge and discharge dynamic range on the spatial and temporal scales that they can resolve. One of the most common approaches for studying groundwater recharge/discharge dynamics uses a baseflow decomposition of the hydrograph (e.g., Rutledge and Mesko 1996, Mau and Winter 1997). This approach is typically used over larger spatial and temporal scales (1000 m$^2$ to >1000 km$^2$, months to decades). Groundwater age and tracer analyses (e.g., Schlosser et al. 1989, Soloman and Sudicky 1991) have been used at intermediate scales (10 m$^2$ to 10,000 m$^2$, months to decades) to characterize recharge/discharge dynamics and to better understand subsurface flow paths. Smaller scale studies (0.1 m$^2$ to 10 m$^2$, days to years) have focused on unsaturated zone lysimeters and plot-scale tracers (Scanlon 1992, Ward and Gee 1997).

Advances in our understanding and predictive capabilities for groundwater recharge/discharge dynamics will require multi-scale, multi-process studies that incorporate geophysical characterization methods. Groundwater fluxes are coupled to climate and land-use conditions through the processes of precipitation, evaporation, transpiration, and infiltration. The active flow zone where groundwater flow and transport occurs at human time-scales remains largely uncharacterized beyond qualitative geological maps. As our ability to exploit groundwater resources has increased from the mid-20th century, there has been increasing realization that groundwater withdrawals and droughts can yield long-term and large-scale impacts on surface flows and aquatic ecosystems. This realization motivates the need for integrated multi-scale, multi-process studies that utilize chemical and physical analysis of groundwater flow to better understand subsurface flow pathways, residence times, and fluxes across media interfaces.

**Airborne high resolution time domain transient electromagnetic surveys (TDEM), Instrument Description:** Since the 1950s there has been an emerging suite of airborne electromagnetic surveying systems (Sorensen and Auken 2004) that have been used for mineral exploration and more recently groundwater mapping. These systems can map the volumetric extents and conductivities of subsurface lithology where contrasts in electrical conductivity are present. TDEM applications also have the potential to identify the presence of contamination in groundwater. A recent helicopter mounted TDEM system proposed by (Sorensen and Auken 2004) termed SkyTEM is illustrated below. The system consists of a 12.5 x 12.5 m$^2$ square loop transmitter mounted on a wooden lattice and a rigidly mounted receiver. The receiver uses two independent computers, one to manage
incoming measurements and the second to control the transmitter while recording the transmitted waveforms, GPS coordinates, laser altitude, and angle (Sorensen and Auken 2004). In very basic terms, the transmitter passes current through the subsurface with a known a priori waveform, the conductance of subsurface hydrologic units will then uniquely modify the initial waveform recorded by the receiver. The modified waveform data are then used to characterize the conductance of subsurface units. Groundwater characterization applications require data processing at time intervals ranging from micro-seconds to milli-seconds.

Figure 4. Illustration of SkyTEM adapted from (Sorensen and Auken 2004).

Accuracy and Precision: Sorensen and Auken (2004) validated the SkyTEM system’s repeatability and accuracy to within 5 % of ground-based TDEMs at sensor flight heights ranging from 7 to 20 m. Field use of the system requires a base station where survey data is transmitted every 2 h during helicopter refueling.

Working Conditions and Environment: An advantage of being airborne is that this system can fly above woodland and vegetation that would otherwise inaccessible to ground surveys. Flying this instrument requires reasonable weather conditions and may be restricted in high winds. 2-D metallic linear features must be avoided as well as power lines. The system is therefore not suitable in urbanized areas.

Deployment and Support: Constraints in the field application of this technology are largely determined by helicopter flight requirements, base station access, and potentially interference from developed structures. Any airborne TDEM system would require PhD-level support for interpretation of data as well as operation and maintenance. Surveys using the SKYtem system are now available from geophysical contractors in the US. Hence the most cost effective use of funding resources is to subcontract this data acquisition.

Costs: The SkyTEM system is operated by the helicopter pilot and since the equipment is outside of the helicopter it reduces operation costs associated with licensing. The SkyTEM hardware cost is approximately $100K neglecting the operational costs associated with the helicopter, pilot, and base station personnel. Pricing is based on several variables such as location, area, terrain, line spacing, final products, but rough estimates for hydrological surveys vary from approximately $75K for 400 line-km to $100K for approximately 1,200 line-km.
Where in the Diagonal (Space/Time): This type of instrumentation creates the possibility of conducting groundwater surveys over large areas (10,000 km²). This means that it could provide regional data at large scales that were previously not accessible.

**Airborne Handheld LiDAR for High Resolution Terrain Mapping, Instrument Description:** Rapidly deployable LiDAR mapping tools would benefit groundwater studies as well as studies of other components of the water cycle by providing improved characterization of terrain and vegetation. These systems would also allow rapid response to events such as rain on snow flooding. As an example, the handheld HELIMAP system combines an airborne laser scanner (LiDAR), a high resolution digital camera, and a global positioning system/inertial navigation system (Vallet and Skaloud 2005).

**Accuracy and Precision:** Using the HELIMAP as an example, the mapping capabilities of the unit can resolve surface features at the decimeter scale for flight heights of up to 500 m (Vallet and Skaloud 2005). This system can be used for mapping spatial scales up to 8 km². Data management requires careful synchronization of measurements from the LiDAR, the GPS/INS systems, and the camera using specialized software and an Ethernet communication, Figure 6.

**Working Conditions and Environment:** The airmobile nature of the instrumentation provides great flexibility in the environments where it can be deployed. Air portable systems also depend on fair weather conditions as the major constraint to flying.

**Deployment and Support:** The light weight and modest size of the unit allow it to be deployed in < 30-min for rapid response surveying for extreme events. In order to minimize mapping errors, care must be taken to dampen the impacts of rotor vibrations on the system (Vallet and Skaloud 2005). Again constraints in the field application of this technology are largely determined by helicopter flight scheduling and costs.

**Costs:** The price of portable LiDAR systems is largely dependent on the choice of off-the-shelf component sensors. Depending on configuration, costs could range from $50K to $100K for systems similar to the HELIMAP.

**Where in the Diagonal (Space/Time):** This type of technology advances research at large spatial scales (~8 km²) while resolving system features at the decimeter scale.
Borehole Development and Subsurface Characterization Suite, Instrument Description: In the context of a mobile facility to support groundwater flux studies, it would be beneficial to provide a mobile drilling tool. Boreholes are necessary for piezometric head measurements as well as ground-based geophysics to characterize porous or fractured media. Any mobile drilling rig must balance the robustness of the drill to operate over a range of hydrogeologic conditions with the need to access numerous remote experimental sites. The Port-a-drill-mini is an example such a system that can be used to drill in a broad range of conditions, http://www.portadrailmini.com/.

The drill can make up to 15 cm diameter boreholes, deep enough to characterize flow in most active aquifers depending on the rock type (<100m). As a reference, the industrial version of the drill costs are ~$15K with basic accessories and has a benchmark drill rate in concrete of approximately 1.8 m h⁻¹. In order to be effective the rig would need to be moved with some form of vehicle (e.g., a track loader and trailer would cost an additional $50 to $75K). In addition, drill and auger bits must be carefully selected based on the media being drilled as well as the feasibility of using injection fluids.

The mobile drill rig would support traditional monitoring of groundwater levels as well as borehole geophysics. Typical borehole geophysical methods include electrical resistivity imaging and borehole radars, requiring insertion of plastic rather than metal access tubes. These instruments range in cost between $50K and $90K, and are used to characterize sub-meter heterogeneities within the subsurface (rf. http://www.sensoft.ca or http://www.heritagegeophysics.com). Electrical resistivity methods use transmitting and receiving electrodes connected to resistivity meters to measure the subsurface structure and flow pathways for groundwater systems. Resistivity surveys can be used to measure the depth of the water table, the extent of groundwa-
ter contamination, and the extent and location of fractures in the subsurface. Surveys can also cover > 10 m², generating 2- or 3-D tomograms (images of resistivity) that resolve subsurface properties at sub-meter spatial resolutions. Borehole logging tools are items that are exceptionally useful and generally deployed to characterize a suite of boreholes for a project. They are usually deployed on a limited basis, once or twice in the lifetime of a project, and tend to have a lot of down time. Therefore this type of equipment would work well as part of a larger suite of instrumentation.

**Networked Sensors, Instrument Description:** Sensor networks are strongly support across subdisciplines. There are 2 basic reasons to have sensors networked, i) to better quantify the spatial heterogeneity of water cycle components, and ii) to have the ability to communicate with and assure data quality from field deployed sensors—all of which are essential in establishing spatial and temporal linkages among scale and across WC components. For example, assessing the spatial heterogeneity in soil meteorological measurements is difficult to accomplish, particularly when the soil environment can change rapidly with punctuated, stochastic events, e.g., precipitation, snow melt, thaw, rapid drought. Coefficient of variation in measured variables can often be large across even small spatial areas. In the other example, assign the data quality for each sensor (array) embedded in a larger network can identify problems that can then be quickly addressed. Moreover, networked sensors and other instrumented platforms (e.g., EC) generate large datasets that have to be managed, quality controlled and subsequently analyzed in a timely fashion. Having the ability to communicate to data acquisition systems and download data from remote locations to a central data repository can facilitate the need for real time data analyses and products.

There are numerous data acquisition systems available on the market today. Communication from these systems to a central repository can be readily accommodated by hard wired technologies, e.g., Ethernet, short haul modems, or multidrop (multiple data acquisition systems queried through a single cable), or wireless technologies, e.g., telephone (cellular or landline), satellite telemetry, and across radio frequency (UHF, VHF, and spread spectrum). Of these existing technologies radio-based methods show promise in that they are low cost, robust in severe environments, adaptable to various applications, and have low power requirements. For example, a 922 MHz spread spectrum radio (model RF411, Campbell Scientific Inc., Logan UT) can be used to link 75 to 100 individual data acquisition systems (CR206, Campbell Scientific Inc.), each measuring 4 to 5 soil variables (temperature, volumetric water content, and others TBD), across a distributed network that can span 1 km². A rapidly emerging area is embedded wireless sensor networks. These are networks of small, low power devices including numerous environmental. Crossbow, Inc. uses the TinyOS and the Mica2 family to provide a complete networking and signal processing system.

**Working Conditions and Environment:** Applicable to most watershed conditions.

**Deployment and Support:** Requires experienced technician or Ph.D. level scientist.

**Costs:** 100 node network $100-200K. Highly dependent on the extent of the network and instrumentation deployed.
4. Proposed Instrumentation Suites

In Section 2.1, the HMF WC group identified two focus areas related to science questions and corresponding measurement needs across relatively large areas and relatively short time intervals (lower right-hand corner of Figure 2) and one area of opportunity associated with the upper left-hand corner of the diagram. If we consider these opportunities in light of the instrumentation identified in Section 3, we can identify instrumentation capable of making measurements at spatial and temporal scales that match the focus areas (Figure 7). The following section presents three current challenge areas. A broad description and specific scientific questions are provided for each challenge area. Instrumentation required to advance scientific inquiry in these areas are considered in light of the spatial and temporal extent, the required measurements, and community input. In addition, a vision of how such instrumentation might be deployed is provided.

![Figure 7](image-url)

Figure 7. Schematic representing space and time process scales. The numbered rectangular boxes correspond to scales over which 1) x-band, 2) LIDAR, 3) LAS/ SODAR, 4) EC/isotope sensor, 5) networked sensors, 6) TDR, and 7) GPR operate. Associated numbers are located in the bottom left-hand corner of each box.
4.1 Water Supply/Droughts/Flood Forecasting

a. Challenge area: Prediction for ungauged basins (PUB); Prediction of groundwater recharge/event runoff, implications of land use change on water supply (e.g., urbanization, irrigation); Prediction of infiltration/runoff partitioning and its spatio-temporal distribution under different soil, topography, vegetation, and precipitation patterns across the watershed/basin. Prediction of watershed concentration and transit of streamflows, including time of travel, associated hydraulic characteristics such as depth and velocities.

b. Science questions/hypotheses: PUB provides an appropriate framework here (see the science plan, Sivapalan et al. 2003). Other examples of science questions: How do land-use and climate changes in watersheds and their concomitant shifts in vegetation and recharge impact water supply and hydrologic extremes? What is the role of the channel network in flood propagation? What role does riparian vegetation have in stream/aquifer interaction? What is the dependence of scaling relationships of floods on the scaling descriptions of topography, vegetation, rainfall, soil properties? What are the “dominant” hydrologic (surface and subsurface flow) processes and the associated “effective” hydrologic/hydraulic parameters at different space-time scales during drying (related to drought) versus wetting (related to flooding) sequence? How do effective soil hydraulic parameters and their scale relationships change with flow direction, geological settings and layering, landscape depositional anisotropy/heterogeneity, and hydrologic boundary conditions? How can rainfall be scaled at scales below those of operational radars (i.e. < 4 km$^2$)? Within the water cycle, what processes dominate long-term drought dynamics? What is the relative importance of local versus regional groundwater recharge in hydrologic extremes? What are the appropriate measurement scales for groundwater recharge when considering water quality, water supply, and hydrologic extremes?

c. Measurements required to address science questions: Subsurface depth to interface, Vadose zone characterization and flow/transport boundary conditions, Precipitation, Soil moisture/pressure, Recharge (inferred)

d. Spatial Extent: 100 m-100 km; Temporal Extent: Hours to Multi Year; Measurement Scale (Resolution): 0.01-100 m at minutes to days. The small spatial scale needed to describe the hydraulic geometry of the channel network that affects the propagation of flow and flooding. Topography needs to be sampled at 1-10 m resolution, rainfall and snow water equivalent at 100-1000m, and discharge at numerous points in the network. Soil moisture at different depths (sub-meter scale) between the land surface and the groundwater table, a primary indicator for determining the irrigation need, drought status, and flood initiation, needs regular (minutes to months) measurements across spatial scales (meters to several kilometers) in a watershed/catchment based on its topography, vegetation,
and soil distribution. Groundwater recharge can be assessed using baseflow decomposition of the hydrograph over large spatial and temporal scales (1000 m² to >1000 km², Months to Decades). Groundwater age and tracer analyses have been used to assess recharge at intermediate scales (10 m² to 10,000 m², Months to Decades).

c. First Tier Suite –
- Networked Atmospheric Sensors
- Networked Groundwater and soil moisture/pressure sensors
- Ground penetrating radar and borehole geophysics
- Mobile radars
- Pressure transducers for stage measurements, hydroacoustic measurements for both periodic, manned measurements and slide-looking, in situ monitoring of streamflow, webcams for PIV of surface velocity estimation, remotely controlled ADV for cross-section bottom profiling.

d. Second Tier Suite:
- Mobile Vadose Zone Laboratory
- Airborne LiDAR
- Airborne high resolution time domain transient electromagnetic surveys
- Airborne passive microwave soil moisture measurement
- Microwave and ground-penetrating radar discharge measurement and monitoring.

g. Approach: We envision deployment of dense networks of in-situ instruments in a nested sampling scheme. The most significant challenge is acquisition of discharge data of a sufficient areal and temporal density to identify and partition the causal influences of precipitation, soil moisture, temperature, and basin characteristics (size, slope, aspect, soils, etc.) and land use on the volumes, rates of flow, and times of transit on the discharge, the materials carried in it, and the sculpting of stream channels. As such there is a need for taking large number of stream discharge measurements to characterize the scaling relationships across different size contributing areas. Networked sensors would figure prominently in this suite including atmospheric measurements that collects information on air temperature, relative humidity, wind speed and direction, barometric pressure, rainfall, solar radiation, ET, and soil sensors to characterize soil moisture/pressure/temperature, surface flow, groundwater flow, and water quality (see Figure 8). Evaporation, Transpiration, and Recharge (ETR Flux Arrays) are illustrated in Figure 8b as having a clustered design with 3-4 wells separated with small enough distance to allow determination of the subsurface water flow direction. The groundwater wells can be collocated with rainfall (Figure 8a), soil moisture/pressure, and ET measurements thus providing plot scale water balance data. Taken together, the Eddy Flux system, the soil moisture flux array, and the piezometer flux array will allow estimation of water balances within the plot-scale volume. An important extension of the flux in northern latitudes will be the cold season processes of snow, ice, and frost. The co-located climate stations, eddy flux towers, groundwater wells and soil moisture/pressure measurements.
can be deployed in a variety of configurations depending on experimental goals. Figures 8c and 8d illustrate stream-reach flux experiments and hillslope scale experiments. Dense rain gage networks (1 gauge per 10 km$^2$) will well complement operational radar data. In cold regions similar dense networks are envisioned to ground-truth and improve the resolution of regional air-based and remotely-sensed surveys of snow water equivalent distribution. For higher resolution rainfall data specialized (research radars) may be needed instead of increasing rain gauge network density. GPR would be used to resolve subsurface properties at sub-meter spatial resolutions. Real-time tomography could be used to enhance recharge estimates.

h. Ties to SAT and survey results: Aligned with the SAT science theme of linkages and feedbacks within the water cycle. Directly informs the SAT’s theme of the human dimension for water cycle interactions with respect to water availability and demand. The suite addresses the four major HMF survey initiatives.

i. Complementary science questions: Can integrated hydrological and atmospheric observations during flood and drought events be used to improve water cycle predictions for future events?

![Figure 8: (a) Climate flux array, (b) Evaporation-Transpiration-Recharge Array, (c) Differential Stream-Reach flux array, and (d) Hillslope flux array. Adapted from (Reed et al. In Review)](image-url)
4.2 Hydrology and Climate/Agricultural and Ecosystem Productivity

a. Challenge area: Prediction of short time scale water transformation at large spatial scales, partitioning of sources to predict water dynamics, surface energy fluxes, and their relationship to system productivity

b. Hydrology science questions: How does land use force local climate? How does soil type affect water fluxes at the land surface? How does soil management affect water fluxes at the land surface? Do currently existing pedo-transfer functions sufficiently represent local soil physical properties for estimating water fluxes at the land surface? What is the spatial correlation structure of land surface soil water content, and how does it compare to the spatial correlation structure of ET? How is antecedent soil moisture flux and vegetation transpiration related to the diurnal cycle of convective hydrological events? What are the predictor variables of plant water stress? How do climate and soil environment inform vegetation productivity? How will changes in winter snow regime ripple through the annual soil water cycle? How do changes in water availability affect the potential for widespread fire, and at what scales? What feedbacks may occur to any of these proposed questions, and at what relevant scales?

c. Measurements required to address science questions: Energy fluxes and the energy balance (latent heat, sensible heat, ground heat, and radiation), Precipitation, meteorological variables in the atmospheric boundary layer, Vadose zone characterization, Soil Moisture, Soil Respiration, Vegetation

d. Spatial Extent: Subwatershed to watershed (500 m - 10 km); Temporal Extent: (weeks to years); Measurement Scale (Grain): 1 m to 1000 m on hrs; Temporal Extent (minutes to weeks). At this space-time scale combination, evapotranspiration can be measured based on water vapor LIDAR measurements several times a day over several days. A nested sampling design is suggested for soil water content measurements close to the soil surface as a key soil variable governing evapotranspiration. For determining its spatial covariance structure and cross covariance with LIDAR measurements (ET), a set of measurements can be taken less than 5 m apart from each other. The number of sampling nests depends on the type of experimental area. At some reference points, soil water content and matric potential should be measured vertically across the vadose zone for calculating actual evapotranspiration.

e. First Tier Suite –

- Series of Evapotranspiration Modules (Eddy flux, LAS, Laser Isotope, Micrometeorological Instrumentation)

- Integrated networked off-grid-capable sensors and supporting monitoring and archival software (Wireless dataloggers capable of monitoring a range of sensors including soil water content, heat, hydraulic and electrical conductivity, rainfall (precipitation), web cams, canopy temperature, surface temperature, snow properties)

- Mobile hemispherically scanning
Water Vapor LIDAR, Snow LIDAR

f. Second Tier Suite:
   • Electromagnetic Survey
   • Mobile radars with atmospheric moisture content as a derived variable
   • Mobile passive microwave (UAV)

g. Approach: We envision routine deployment of instruments that are capable of simultaneously providing high spatial resolution measurements of fluxes and stores of water and energy of vadose zone control volume. A key to advancing conceptual models is the ability to tracing water vapor in evaporative fluxes to sources and sinks (e.g., transpiration versus evaporation, deep water versus shallow water). Instrumentation should be capable of making measurements at subwatershed to watershed scales with a focus on sampling agricultural fields, natural environments, and suburbanizing water supplies. A nested design of point measurements is sought that can be embedded within footprints and path lengths of the flux instrumentation.

h. Ties to SAT and survey results: Links to all three science themes. Links to three Survey Initiatives including 1) Improving the integration between measurement and modeling methods, 2) Improving spatial resolution of measurements, and the ability to make more and better measurements through distributed sensor networks.

i. Complementary science questions: What are the local controls on the atmospheric boundary layer evolution? How do land surface water and conditions effect quantities and transportation air pollution? How is antecedent soil moisture and vegetation transpiration related to the diurnal cycle, intensity and location of mesoscale atmospheric events? How are the storage and exchange of carbon related to the storage and the exchanges of energy and water? Do the spatial patterns of evapotranspiration and soil surface water content reflect zones of different biomass productivity?

Opportunistic Measurements – Extreme High Flow Events (Prediction and transformation)

a. Challenge area: Hydrologic events of extreme magnitude or having significant ecological or geomorphic impact (e.g., hurricane derived floods). In brief, this suite seeks to provide instrumentation to support the reactionary deployment of mobile monitoring and measurement systems to supplement existing monitoring installation at locations where extreme hydrologic events are underway or are anticipated in the immediate future. The prime examples of extreme hydrologic events for which opportunistic measurements are possible include the approach and landfall of hurricanes and floods resulting from intense rains yielded by frontal systems or by rapid melt of abnormally high accumulations of snow.

b. Science questions: How are large magnitude floods distributed in space and time? Which hydrologic phenomena account for the largest contributions of sediment and chemical load and control the formation and change of channels, beaches, and landscapes? What are the actual magnitudes of floods and how transferable are uncalibrated extensions of empirical re-
lations? For example, the magnitude of the largest floods are most often derived from extension of stage-discharge ratings beyond those flows measured directly through application of simple one-dimensional models based on post-storm measurements of channel features and water slopes that, because of the channel scour and fill that occurs throughout the flood, rarely represent the true channel geometry at any specific time during the flood. How do bed conditions evolve during floods? How are dunes formed and sheared? How does aquatic habitat alter in response to periods of intense environmental stress? How to we extend the prediction of hydrologic phenomena beyond ranges measured during more “normal” conditions?

c. Measurements required to address science questions: Precipitation, streamflow, subsurface characterization (vadose, interface depth, recharge) and channel characterization

d. Spatial Extent: In one sense, the challenges associated with opportunistic measurements are inversely proportional to the scale of the watershed and aerial extent of the hydrologic event. Notice of hurricanes is now routinely provided days, even weeks in advance, although the specific location of affected areas and the strength of the event may not be known until a few days or even hours in advance of landfall. The same can be said of rapid snow melt. But convective storms spawned by frontal systems give rise to floods with less advance notice or specificity. Consequently, leads times to prepare and deploy equipment is adequate in a general sense for larger events, but may be less so for smaller events that quickly build, crest, and decline. Getting mobile equipment established at specific locations will require assumption of some predictive risk, occasionally resulting in dry runs. To reduce this risk, deployments should focus on a small number of locations within the impact area and feature observations of watersheds ranging from 10-100km. Most deployments might range in length from a few hours to a few days, but some could last a few (2-4) weeks. Measurement scale varies across the spectrum of monitored parameters. Discharge measurement, while indicative of upstream watershed contributions, are relatively site specific (covering a single cross-section) and requiring only a few minutes each.

e. First Tier Suite:
• X-Band Mobile Radars
• Hydroacoustic technologies such as the Acoustic Doppler Current Profilers
• Networked Gages (visible/IR camera)
• Ground Penetrating Radar

f. Second Tier Suite:
• Network sensors to monitor soil water condition
• LIDAR for channel network characterization and generation of snowpack data
• Clusters of Phased Array Acoustic Doppler Velocity Meters (ADVM)
• Experimental side-looking or downward looking radars operated from bridges, river banks, or helicopters to provide direct measurement of
surface-velocities and channel cross-sections

g. Approach: By their very nature, opportunistic measurements are difficult to anticipate. But with modern technology, both that are in hand and on the near-term horizon, together with careful logistical planning and properly staffed infrastructure, it is possible to conceive of a network of cached instruments that could be deployed to areas impacted by floods at short notice and for relatively brief periods of time. The core requirements are high resolution rainfall and streamflow data complemented by measurements of subsurface and soil properties. One or more mobile X-Band precipitation radars would be deployed to monitor precipitation over an extensive area (~1000 km²). Portable rain gauges or optical disdrometer platforms would be used to support radar observations. ADCP would be used to rapidly measure flood flows in a variety of stream settings. Streamflow and channel bathymetry measurements would be repeated over the course of a rise and fall of a flood hydrograph. Deploying the ADCP in a repeat sinusoidal pattern, during a flood would enable measurements of flow at multiple locations through time, but could also be used to build maps of changing bathymetry throughout the event. Inexpensive stage sensors and cameras could be used to collect concurrent water level data and, if deployed along reaches of a stream, could be used to define water, energy slopes, and river ice conditions. The cameras can provide images used for estimation of surface velocity fields and subsequently, when combined with ADCP data on cross-sectional bottom profiles, discharge.

h. Ties to SAT and survey results: Links to all three science themes and meets the challenge of campaign style measurements. Links exist to all HMF survey initiatives with particular opportunities to improve the integration between measurements and modeling methods.

i. Complementary science questions: How does connectivity to uplands impact stream biogeochemistry? How do coastal storm surges and flood pulses combine to cause inland flooding?
5. Potential CUAHSI Water Cycle Instrumentation Synergies

The HMF Biogeochemistry’s and Geophysics’s parallel white papers identify numerous instrumentation and measurement resources. Several instruments identified by the Geophysics group are explicitly included in two of the WC instrumentation suites. The broader science themes and questions imply connections to the biogeochemistry effort as well as opportunities for complementary vegetation and aquatic biology measurements. These connections would be well served by expanding the scope of existing suites or by creating new suites.

Many opportunities exist for the HMF to establish collaborative partnerships across disciplines outside of CUAHSI initiatives. The HMF would be well served by leveraging existing expertise and instrumentation within Earth system science communities and across engineering disciplines at universities and federal agencies. The following section identifies existing and compelling potential partners. It is not intended to provide an exhaustive list, but to demonstrate the breadth of prospective collaborators. Potential synergies for large instruments such as LIDAR and passive microwave platforms are presented first, then other measurement facilities, such as NCAR, USGS HIF and NCALM, are identified, and organizations that have existing infrastructure, including the USDA watersheds and the Florida Coastal Monitoring Program, are presented as examples of how HMF instruments and measurements could augment. Finally we consider scientific measurement campaigns and other National level consortia aimed at enhancing observation and measurements to improve understanding of the environment.

5.1 Large Instruments (LIDAR and Passive Microwave)

A large number of ground-based L band sensors are currently available throughout the remote sensing scientific community. These include the ComRAD, UFLMR, TMRS, MOSS, TSMR, and Iowa systems in the USA, the EMIRAD, ELBARA, PMR, and LEWIS systems in Europe, and the NSMR, SPMR, and RADIUS systems in Russia/USA. Some instruments, like the STAR-Light system in the USA and the SLFMR system in Australia, have been designed primarily to fly on light aircraft but can be adapted to operate on a tower or boom truck platform. There is also one system, the USA’s MACS that currently flies on an unmanned UAV helicopter. Table 2 reviews the available systems. Figure 9 shows two examples of these systems.
<table>
<thead>
<tr>
<th>Instrument</th>
<th>Location</th>
<th>Active / Passive</th>
<th>Platform</th>
<th>Point of Contact</th>
</tr>
</thead>
<tbody>
<tr>
<td>EMIRAD</td>
<td>France</td>
<td>Passive polarimetric</td>
<td>Tower</td>
<td><a href="mailto:wigneror@bordeaux.inra.fr">wigneror@bordeaux.inra.fr</a></td>
</tr>
<tr>
<td>ELBARA</td>
<td>Switzerland</td>
<td>Passive dual pol</td>
<td>Tower</td>
<td><a href="mailto:mike.schwank@env.ethz.ch">mike.schwank@env.ethz.ch</a></td>
</tr>
<tr>
<td>PMR</td>
<td>England</td>
<td>Passive dual pol</td>
<td>Zipper truck</td>
<td><a href="mailto:ijd@mail.nerc-essc.ac.uk">ijd@mail.nerc-essc.ac.uk</a></td>
</tr>
<tr>
<td>LEWIS</td>
<td>France</td>
<td>Passive dual pol</td>
<td>Tower</td>
<td><a href="mailto:yann.kerr@cesbio.cnes.fr">yann.kerr@cesbio.cnes.fr</a></td>
</tr>
<tr>
<td>ComRAD</td>
<td>Maryland</td>
<td>Active/passive</td>
<td>Boom truck</td>
<td><a href="mailto:peggy.c.oneill@nasa.gov">peggy.c.oneill@nasa.gov</a></td>
</tr>
<tr>
<td>TMR S</td>
<td>Michigan</td>
<td>Passive dual pol</td>
<td>Boom truck</td>
<td><a href="mailto:deroo@eecs.umich.edu">deroo@eecs.umich.edu</a></td>
</tr>
<tr>
<td>UFLMR</td>
<td>Florida</td>
<td>Passive dual pol</td>
<td>Tower</td>
<td><a href="mailto:jasmeet@ufl.edu">jasmeet@ufl.edu</a></td>
</tr>
<tr>
<td>Iowa-LR</td>
<td>Iowa</td>
<td>Passive dual pol</td>
<td>Boom lift</td>
<td><a href="mailto:bkh@iastate.edu">bkh@iastate.edu</a></td>
</tr>
<tr>
<td>TSMR</td>
<td>Colorado</td>
<td>Passive H pol</td>
<td>Tower</td>
<td><a href="mailto:valery.zavorotny@noaa.gov">valery.zavorotny@noaa.gov</a></td>
</tr>
<tr>
<td>SPMR</td>
<td>Alabama</td>
<td>Passive single pol</td>
<td>Boom truck</td>
<td><a href="mailto:frank.archer@msfc.nasa.gov">frank.archer@msfc.nasa.gov</a></td>
</tr>
<tr>
<td>MACS</td>
<td>Alabama</td>
<td>Passive single pol</td>
<td>UAV helicopter</td>
<td><a href="mailto:frank.archer@msfc.nasa.gov">frank.archer@msfc.nasa.gov</a></td>
</tr>
<tr>
<td>NSMR</td>
<td>Russia</td>
<td>Passive single pol</td>
<td>small A/C</td>
<td><a href="mailto:ahaldin@sdb.ire.rssi.ru">ahaldin@sdb.ire.rssi.ru</a></td>
</tr>
<tr>
<td>RADIUS</td>
<td>Russia</td>
<td>Passive multiband</td>
<td>small A/C</td>
<td><a href="mailto:anatoli.shukotko@email.aamu.edu">anatoli.shukotko@email.aamu.edu</a></td>
</tr>
<tr>
<td>SLFMR</td>
<td>Australia</td>
<td>Passive V pol</td>
<td>small A/C</td>
<td><a href="mailto:mal.heron@jcu.edu.au">mal.heron@jcu.edu.au</a></td>
</tr>
<tr>
<td>STAR-light</td>
<td>Michigan</td>
<td>Passive LHC pol</td>
<td>small A/C</td>
<td><a href="mailto:deroo@eecs.umich.edu">deroo@eecs.umich.edu</a></td>
</tr>
<tr>
<td>MOSS</td>
<td>Michigan</td>
<td>Polarimetric radar</td>
<td>Tower</td>
<td><a href="mailto:mmoghadd@eecs.umich.edu">mmoghadd@eecs.umich.edu</a></td>
</tr>
</tbody>
</table>

Table 2. Available L Band Ground-Based Microwave Instruments (source O’Neill)

Water vapor lidars (see also Section 3.3), which typically provide remotely sensed water vapor mixing ratio at specified range gates and over a specified range, have not been integrated into hydrologic scientific research despite their potential to contribute significantly to the key water cycle research topics per Figures 1 and 2. Current water vapor measurement techniques using lasers can be classified in two categories: 1) Raman (WVR) and 2) DIAL (Differential Absorption Lidar, WVD). The first measurements were made via these techniques 40 years ago (Schotland 1966, Cooney 1970). Geoscience research has ap-
plied these instruments over the last 25 years, with significant advances occurring over the last 10 years. Water Cycle research would significantly broaden the spatio-temporal measurement scales with routine access to these instruments. Existing water vapor lidars have sample rates of 10s-100s Hz and range gates of 1-100s m. Existing water vapor lidars are mobile, capable of nearly continuous operation for months at a time and utilize a hemispheric scanning radius of generally 1-10 km, although seldom incorporating all of these capabilities. A number of applications are airborne. Existing system’s specifications vary depending on range gate size and averaging time (Table 3). The water vapor mixing ratio accuracy is in the range of 5-10% or at least 0.1 g kg⁻¹ (Wulfmeyer and Walther 2001a, b). The DLR WVD (see Figure 10), has additional dynamic and horizontal range because it utilizes differential absorption based on two absorbing wavelengths.

Currently, the scanning systems are only available through research institutions, but promising commercial eye-safe microlidar systems are now emerging from Sigma Space Corporation (US), Leosphere (France) and Raymetrics (Greece). There is potential for the HMF to identify and facilitate access to an existing system prior to pursuing the development of a water vapor lidar optimized to hydrology community requirements (Wulfmeyer and Walther 2001a).

Figure 10: The promise of high resolution water vapor DIAL measurements from the recent International H2O Project 2002 (IHOP). Pictured are measurements of atmospheric boundary layer water vapor mixing ratio and Doppler lidar vertical velocity measurements (top two figures) and the resulting vertical water vapor fluxes (for details see Weckwerth and Parsons (2006) and www.eol.ucar.edu/dir_off/projects/2002/IHOPwsOct03/kiemle.ppt.
<table>
<thead>
<tr>
<th>Lidar Type</th>
<th>Location/Contact</th>
<th>Wavelength</th>
<th>Status/Range Gate Size (m)</th>
<th>Type</th>
</tr>
</thead>
<tbody>
<tr>
<td>WVD</td>
<td>NASA Langley E. Browell</td>
<td>815 nm</td>
<td>Operational/300</td>
<td>Non-scanning Browell et al. 1979</td>
</tr>
<tr>
<td>WVD</td>
<td>DLR Germany G. Ehret</td>
<td>724 nm, 830 nm, 940 nm</td>
<td>Operational/300</td>
<td>Vertically pointing Ehret et al. 1993</td>
</tr>
<tr>
<td>WVD</td>
<td>CNRS Paris C. Flamant</td>
<td>730 nm</td>
<td>Operational/300</td>
<td>Pointing Bruneau et al. 2000</td>
</tr>
<tr>
<td>WVD</td>
<td>U. Hohenheim Germany V. Wulfmeyer</td>
<td>532 nm</td>
<td>Under development</td>
<td>Scanning Wulfmeyer and Walther 2001b</td>
</tr>
<tr>
<td>WVD</td>
<td>NOAA Boulder Janet Machol</td>
<td>823 nm</td>
<td>Under dev/250-500</td>
<td>Scanning Machol et al. 2004</td>
</tr>
<tr>
<td>WVD</td>
<td>U. Hamburg Germany K. Ertel</td>
<td>820 nm</td>
<td>Operational/---</td>
<td>Vertically pointing</td>
</tr>
<tr>
<td>WVD</td>
<td>Sigma Space Corp.</td>
<td>Telecomm</td>
<td>Under development</td>
<td>N/A</td>
</tr>
<tr>
<td>WVD</td>
<td>U. Montana</td>
<td>Telecomm</td>
<td>Under development</td>
<td>Vertically pointing</td>
</tr>
<tr>
<td>WVD</td>
<td>UNIBAS, Potenza, Italy P. Di Girolamo</td>
<td>355 nm</td>
<td>Operational</td>
<td>Vertically pointing Di Girolamo et al. 2003</td>
</tr>
<tr>
<td>WVR</td>
<td>NASA Goddard Melfi, Whitman</td>
<td>351 nm, 355 nm</td>
<td>Operational/75</td>
<td>Scanning Whitman et al. 1992</td>
</tr>
<tr>
<td>WVR</td>
<td>LANL Dan Cooper</td>
<td>248 nm, 351 nm</td>
<td>Operational/2-75</td>
<td>Scanning Eichinger et al. 1999</td>
</tr>
<tr>
<td>WVR</td>
<td>DOE ARM CART (Oklahoma) H. Revercomb</td>
<td>355 nm</td>
<td>Operational/75</td>
<td>Vertically pointing Revercomb et al., 2003</td>
</tr>
<tr>
<td>WVR</td>
<td>Observatorie de Haute Provence</td>
<td>532 nm</td>
<td>Operational/100</td>
<td>Vertically pointing Cahen et al. 1982</td>
</tr>
<tr>
<td>WVR</td>
<td>Howard University D. Venable</td>
<td>355 nm</td>
<td>Operational/75</td>
<td>Vertically pointing Venable et al. 2005</td>
</tr>
<tr>
<td>WVR</td>
<td>Leosphere (France)</td>
<td>355 nm</td>
<td>Commercial/30 m</td>
<td>Pointable</td>
</tr>
<tr>
<td>WVR</td>
<td>Raymetrics (Greece)</td>
<td>N/A</td>
<td>Emerging</td>
<td>Vertically pointing</td>
</tr>
<tr>
<td>WVR</td>
<td>Sigma Space Corp. (US)</td>
<td>523/532 nm</td>
<td>Emerging/15-75</td>
<td>Vertically pointing</td>
</tr>
<tr>
<td>WVR</td>
<td>EFPL, Lausanne, Switzerland</td>
<td>266 nm</td>
<td>Operational/90</td>
<td>Vertically pointing</td>
</tr>
</tbody>
</table>

Table 3. Available LIDAR Instruments (source: G. Poulos)

5.2 National Center for Atmospheric Research (NCAR)

The NCAR Earth Observing Laboratory (EOL) has provided advanced atmospheric observing systems and support services for geoscientific research for over 30 years. EOL’s mission is to advance the frontiers of research technology and field deployment techniques and to enable efficient execution of multi-disciplinary investigations necessary for a comprehensive understanding of the atmosphere, environment, and weather. EOL is sponsored by the National Science Foundation through the Geosciences Directorate. The technologies that it develops and the equipment that it deploys are NSF facili-
ties. Other NSF facilities reside at Universities throughout the country, including, for example, the Colorado State University CHILL S-band radar, and the University of Wyoming King Air research aircraft. The equipment operated at these NSF Facilities is available to any NSF geosciences researcher as well as other research institutions. The Hydrologic Sciences community has the opportunity to leverage these resources and draw upon this long-standing experience in the creation of an optimized Hydrologic Measurement Facility.

EOL and NCAR staff have recently cooperated with various CUAHSI participants, including the HMF committee and individual long-term hydrologic observatories (LTHO) participants as an atmospheric science partner in potential observatories. EOL expertise encompasses many areas of relevance to the HMF efforts including networked, on-off-grid surface flux and energy balance facilities, transportable and mobile multi-frequency precipitation and wind profiling radars (including QPE and precipitation identification), scanning eye-safe aerosol and water vapor lidars (under development), mobile sounding systems and research aircraft. These systems are maintained, calibrated, deployed, and data quality controlled by approximately 160 staff for field efforts in all environments across the globe. EOL has active, substantive development programs in all of the above technology areas and is supported by a major cyberinfrastructure program, field deployment logistic team and advanced design and fabrication services.

In addition to the complementary instrumentation, the NCAR staff is a potential advisory resource for the HMF. NCAR EOL, in conjunction with NSF and the other NSF facilities, has developed rigorous procedures for the allotment of facilities and related services on a competitive basis to geoscientific researchers. On the basis of this NSF Geosciences structure, we may conclude that a similarly rigorous process will need to be implemented by the HMF for the distribution of its facility suite. These procedures, as well as a description of the NSF Facilities and other components of EOL are described at www.eol.ucar.edu.

5.3 USGS Hydrologic Instrumentation Facility (HIF)

As part of its mission the USGS operates long-term hydrologic networks that monitor the Nation’s water resources and provides the essential information needed for their management. A key element of this data-collection operation is the USGS Hydrologic Instrumentation Facility (HIF), located at Stennis Space Center, Mississippi (http://www.hif.er.usgs.gov/public/). The HIF operates a warehouse rental and sales operation of over 1000 instruments and related items for supporting USGS surface-water, water-quality, and ground-water data-collection activities. Warehouse items include velocity meters, acoustic Doppler current profilers (ADCPs), water level sensors, water quality sondes, rain gages, sediment samplers, data collection devices (data loggers, GOES transmitters), and numerous other pieces of measurement and recording equipment. The HIF rental program has over 7,000 items to lease to customers within the USGS and with other Federal agencies.

Recently CUAHSI and the USGS signed a Cooperative Research and Development Agreement (CRADA). Under this CRADA, coordination of USGS programs and CUAHSI will occur at a variety of levels with a strong focus on areas instrument procure-
ment, development, and testing. To support this effort, a CUAHSI-HIF equipment loan program is being developed on a pilot project basis. The principal benefits of the program include potential cost-savings, better data consistency, and increased instrument reliability.

Additionally, the HIF provides extensive climate-controlled facilities for testing of instruments through cycles of extreme temperatures, humidity, and pressure. Water-quality instruments undergo various performance tests in environmentally-controlled chambers against certified reference standards. The HIF is an authorized repair representative for several makers of satellite telemetry instrumentation, sensing, and recording equipment. The HIF routinely tests instruments for SD-12 compliance, electronic power, and radio transmission protocols. The HIF operates a 35,000 sq. ft indoor hydraulics laboratory and a 30 acre outdoor floodplain simulation facility. A towing tank and submerged jet tank are used to test and calibrate instruments that measure water velocity by the principle of cup rotation, drag, Doppler effect, acoustic signal, electromagnetic field, deflection, or other means.

5.4 National Center for Airborne Laser Mapping (NCALM)

The National Science Foundation’s Division of Geosciences, Instrumentation and Facilities Program funds the National Center for Airborne Laser Mapping (NCALM). NCALM is operated jointly by the R. Shrestha, Department of Civil & Coastal Engineering, College of Engineering, University of Florida (UF) and W. Dietrich, the Department of Earth and Planetary Science, University of California-Berkeley (UCB). NCALM uses the Airborne Laser Swath Mapping (ALSM) system jointly owned by UF and Florida International University (FIU), based at the UF Geosensing Engineering and Mapping (GEM) Research Center. NCALM uses state-of-the-art laser surveying instrumentation and GPS systems, which are installed in a Cessna 337 Skymaster twin-engine aircraft. ALSM data are used to produce highly accurate three-dimensional, digital topographical maps of large land surface areas. Additional information on NCALM is provided at http://www.ncalm.ufl.edu/.

Similar to NCAR equipment, a NSF Principal Investigator (PI) can request additional funds to support NCALM ALSM (LIDAR) data collection. NCALM provides all necessary field crews and equipment for the ALSM data collection. It processes, calibrates, analyzes, validates and produces products of the first Surface and the bare Earth. In addition, NCALM provides opportunities for PIs and graduate students to participate in ALSM planning, data collection, data reduction and analysis. NCALM has also set aside “seed money” for three to five demonstration projects each year by graduate students.

5.5 Watershed Networks

Currently, many watersheds have routinely provided baseline streamflow, rainfall, and meteorological data. These watersheds provide ideal sites to deploy HMF equipment. The USDA Watershed Network is one example of a national network with a long history of baseline data. The watershed network and its associated database cover an area that includes 23 states. Many USDA watersheds have collected data for more than 30 years and offer a unique long term data resource (Slaughter et al. 2001). Currently more than 140 sub-watersheds are operated by the Agricultural Research Service (ARS) ranging in
size from 0.2 hectares to over 600 km² (Goodrich et al. 2000). The locations of the major USDA watersheds and their climatic regions are illustrated in Figure 11. Collaboration with these facilities could enhance the data collection and augment campaign style measurements with long term data. Other potential partners include the Long Term Ecological Research Network (LTER), AmeriFlux, and USGS watersheds.

5.6 The Florida Coastal Monitoring Program (FCMP):

The Florida Coastal Monitoring Program (FCMP) was initiated in 1999 to conduct in field hurricane wind data collection by PI, K. Gurley, Associate Professor, University of Florida, Department of Civil and Coastal Engineering. The purpose of the FCMP is to directly quantify the wind loads experienced by residential structures impacted by hurricane winds, and to evaluate the effectiveness of commonly used retrofit-type mitigation measures on residential construction. The FCMP uses a campaign approach that is synergistic to the HMF Opportunistic Measurements suite. The FCMP PIs are potential collaborators for HMF Opportunistic Measurements initiatives. In addition, the FCMP PIs have significant experience.

The FCMP instrumentation consists of a fleet of five portable wind towers and 32 instrumented homes along the Florida coastline. Figure 12 shows one of the portable wind towers (left) and one house being readied to collect pressure and wind speed data (right). Each of the five 10 m mobile wind monitoring towers is instrumented with fixed anemometer arrays capable of measuring wind velocity at both the 5 and 10 m levels. The towers also collect barometric pressure, temperature, rainfall and humidity. The data collection software is flexible enough to accommodate additional instrumentation to expand the dataset. The FCMP tower data collection system provides real-time wind speed data to a website. Each house is outfitted for installation of pressure sensors on the roof, an anemometer on the roof, and a camera in the yard of the house that is wired to a time-lapse VCR. When a tropical storm or hurricane is predicted to make landfall, FCMP teams deploy to install pressure sensors on the instrumented houses and to erect the mobile wind towers nearby.
5.7 Field Campaigns, Past and Future

Hydrological scientists have some experience engaging in national and international field experiments that draw together University and agency scientists and their students for intensive campaigns. One long-standing and highly productive example is the series of soil moisture experiments that includes Washita’92, Southern Great Plains Experiments (SGP) SGP97 and SGP99, and soil moisture experiments (SMEX) in 2002, 2003, 2004, and 2005 (http://www.ars.usda.gov/Research/docs.htm?docid=8974). These experiments have sought to answer science questions and to serve as test beds for aircraft and satellite passive microwave instruments. To examine soil moisture variability within remote sensing footprint, a large number of ground-based in-situ and hydrometeorological instruments are deployed during a series of experiments. Experiments are conducted campaign style with intensive monitoring and sampling for periods lasting from several weeks to months.

Another example from the past is the Cooperative Atmosphere-Surface Exchange Study (CASES Lemone et al. 2001, CASES-99, Poulos et al. 2002) and the co-located Atmospheric Boundary Layer Experiment (ABLE), which focused measurement efforts in the Walnut River watershed, southeastern Kansas. Atmospheric and other earth science instrumentation were deployed at the watershed scale for multiple years. Three campaign-style sub-experiments were executed.

Another example is the Sierra Hydrometeorological Atmospheric Rivers Experiment (SHARE, see http://www4.ncsu.edu/~seyuter/share_files/060113SHAREspo.pdf and http://www.wrh.noaa.gov/hydroscience/Wed.PM/HMT_HydroConf_final_MRalph_5Oct05.ppt). SHARE is located on the North Fork of the American River, west of the Sierra Nevada in California. As described in the SHARE documents, a suite of mobile and stationary multi-frequency precipitation radars, overflying precipitation radars, wind profilers, sounding systems, GPS water vapor sensors, rain/SWE gauges, surface energy balance and other supporting equipment is planned for December 2007 and January 2008.

Figure 12: An FCMP tower deployed before hurricane Frances landfall (left), and a house in the Panhandle being readied to collect pressure and wind velocity data prior to Ivan (right). (Source: K. Gurley)
5.8 Collaborative Large-Scale Engineering Analysis Network for Environmental Research (CLEANER)

The HMF water cycle instrumentation has significant potential for enhancing our understanding and management of water resources across a gradient of environments from natural to urban. The CUAHSI HMF will explicitly support hydrologic science and can foster emerging collaborations between the hydrologic science and environmental engineering communities. The environmental engineering community has proposed the Collaborative Large-Scale Engineering Analysis Network for Environmental Research (CLEANER) http://cleaner.ncsa.uiuc.edu/about/ initiative, which seeks to develop a large national network of environmental field facilities to better understand the transport dynamics, impacts, and engineered solutions to large scale pollution problems (e.g., hypoxia in the Chesapeake Bay). There is an emerging effort between CUAHSI and CLEANER to build a unified WATERS Network (WATer and Environmental Research Systems Network) to advance our understanding of the impacts that humans have on complex environmental systems.

5.9 National Ecological Observatory Network (NEON)

NEON was formed to provide a geographically distributed infrastructure to enable scientists to interdisciplinary study current environmental and ecological challenges. Implementation of NEON is still nascent though extensive progress has been made outlining science and education goals, and agency planning activities. NEON is designed to operate at real-time and at all levels of temporal and geographic scales to estimate regional to continental-level ecological structure, function and processes. NEON’s goals include all levels of biological activity. The intrinsic relationships with water, energy balance and geomorphology makes NEON a natural partnership for some HMF activities. Currently, NSF-NEON program officers ensure direct coordination with other NSF observatories and network, e.g., CUAHSI (www.nsf.gov/bio/budget/bio_bdg05/neon05.pdf).
6. Strategic plan

6.1 Priority Instrumentation

This report identified three broad research focus areas and supporting instrumentation suites: 1) Water Supply/Droughts/Flood Forecasting, 2) Hydrology and Climate/Agricultural and Ecosystem Productivity, and 3) Opportunistic Measurements - Extreme Events (Prediction and transformation). Immediate opportunities exist for the first two focus areas. All first tier instruments are perceived as being high priority and well poised to make a significant impact by the hydrological sciences community.

The third area, Opportunistic Measurements, is of considerable interest to the HMF. Successful implementation could transform the science of hydrology, have an important and direct impact on the welfare of U.S. citizens, and provide significant visibility for the scientific community. However, a high return on this investment will require additional efforts to further develop this concept. Potential activities include community planning workshops to refine the concept, identification of lead PIs and agency cooperators, and pilot studies. As further planning activities are required, the suite of instrumentation corresponding to Opportunistic Measurements is not considered to be an immediate priority for acquisition. The HMF WC strongly encourage that supporting activities begin as soon as resources allow.

The initial set of instruments to be proposed should be those that best meet the eight criteria outlined in section 1.4. Additionally, instruments that meet these criteria and are able to make measurements for more than one focus area should be prioritized. Several instruments were identified in multiple suites and can provide an opportunity to leverage resources. These include networked sensor arrays, mobile precipitation radar, evapotranspiration flux suites, electromagnetic surveys, and passive microwave sensors.

The first three instruments have a high likelihood of immediate success as they meet all the criteria established in section 1.4. Electromagnetic survey development is clearly valuable, but it will likely be championed by the geophysics community. Passive microwave sensors are challenged by the probable lead time between funding and deployment. As they are not commercially available, the sensors would be built and tested after funding, potentially delaying deployment.

The present model is that instruments will be obtained through competitive proposals submitted to existing NSF funding programs and other grant providing agencies. We would encourage an interagency agreement to advance these goals and funding opportunities. To submit these proposals, instrumentation must be put forth by both the HMF and one or more PIs from CUAHSI Universities. The vision is that the PI(s) will be responsible for the day to day instrumentation support required to conduct scientific research at their watersheds of interest as well as those locations identified by other members of the scientific communities. In return for the PI(s)’ collaboration, the HMF will provide ancillary support that potentially includes proposal development, oversight of collaborative agreements and arrangements, and outreach activities. This arrangement is envisioned to be a partnership between the HMF and the instrument PIs. The success of this model is predicated on identifying PIs who are vested in the HMF concept. As this effort is a trial approach that will likely evolve over the next few years, the first PIs’ visionary, communicative, and collaborative skills are particularly
important for project success. Thus, while a series of instruments have been identified, the instruments require a sponsor to strongly advocate for the instrument and the science. The identification of a strong sponsor should be given significant consideration in the selection of the first suite of instruments proposed.

6.2 HMF Challenges

The HMF WC committee was tasked with identifying instrumentation and technologies that would significantly enhance the measurement of fluxes and storages in the water cycle. The successful acquisition and deployment of these instruments requires the development of a long-term vision of instrumentation support by the HMF. The HMF WC committee identified a number of roles that the HMF should consider fulfilling. These are described below:

1. The HMF should support the acquisition of instrumentation. This will require the HMF to establish a standard set of rules regarding the relationship between the PI and HMF. The HMF should routinely conduct planning workshops to communicate current instrumentation priorities and the HMF rules. Depending on the community response, the HMF may wish to request preproposals to identify instrument PIs. During the instrument proposal preparation, the HMF should provide support in any manner deemed to enhance the successful submission.

2. The HMF should develop an infrastructure to manage the existing HMF instruments. As part of this process, review procedures need to be created. The HMF should be prepared to support community access to instruments including contracts negotiation, insurance, and maintenance. The HMF also needs to be a resource to science PIs who are seeking to use HMF instrumentation and who require information to develop proposals.

3. The HMF should establish data archiving capabilities and procedures. The proposed instrumentation will generate large data streams that need to be adequately stored. In addition, the data will likely be valuable beyond initial research activities. The CUAHSI community should have a reasonable level of access to the data. In addition, consistent standard should be taken to allow for synthesis activities across watersheds.

4. The HMF should develop instrumentation partnerships for HMF instruments and instruments owned by external agencies. As part of this process, potential collaborators will need to be identified and engaged. An initial focus of these partnerships might seek to provide access to large, expensive instrumentation such as LIDARs and instruments deployed on aircraft. The HMF may also wish to facilitate communication regarding pending field campaigns.

5. The HMF should conduct outreach to the CUAHSI community. Critical to this effort is a coordinated plan for transferring knowledge about HMF instruments through workshops, websites, and publications. Outreach may also include identifying and coordinating parallel instrument deployment opportunities. Additionally, the HMF should routinely engage the community and seek their feedback.
6. The HMF should provide vision for present and future instrumentation opportunities. This will require routinely reviewing and updating instrumentation and suites. Successful acquisition and deployment may result in the HMF expanding the existing instrumentation scope beyond that proposed here.

In the immediate future, the HMF is advised to consider each of these items and develop an action plan to implement them. The required effort will yield significant dividends and provide the foundation necessary for a success community instrumentation resource.
References


Resour. 29:369-381.


modeling of unsaturated flow with areal average evaporation and surface soil moisture as 
estimated from remote sensing feasible? J. Hydrol. 143: 125-152.

1993b. Estimation of regional effective soil hydraulic parameters by inverse modeling. in: 
D. Russo and G. Dagan (eds.) Water flow and solute transport in soils. Springer-Verlag, 
Berlin, pp. 211-231.

calculating potential evaporation in regional and global water balance models. Water 
Resour. Res. 32: 2315-2321.

Gage, K.S., C.R. Williams, P.E. Johnston, W.L. Ecklund, R. Cifelli, A. Tokay, and D.A. 
Applied Meteorology 39: 2209-2222.

contributions to Tropical Rainfall Measuring Mission (TRMM) ground validation field 


variability in the tropics, Journal of Geophysical Research-Atmosphere 101(D21): 26165-
26181.


Research Service experimental watersheds and watershed program. Eos Trans. AGU, 


