Bridging river basin scales and processes to assess human-climate impacts and the terrestrial hydrologic system

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[1] The increasing expression of human activity, climate variability, and climate change on humid, terrestrial hydrologic systems has made the integrated nature of large river basins more apparent. However, to date, there is no instrument platform sufficient to characterize river basins' hydrologic couplings and feedbacks, with many processes and impacts left almost entirely unobserved (e.g., snowmelt floods). Characterization at the river basin scale will require a more holistic vision and a far greater commitment from the environmental science community. It will require new designs and implementation of integrated instrumentation, a new generation of models, and a management framework that clearly addresses the human-climate-terrestrial interactions impacting our watersheds and river basins. Initially, we propose that existing "similarity classifications" (e.g., regional soil, geologic, ecologic, hydrographic digital products) can provide a starting point for organizing historical data and initiating a long-term adaptive, multiscale observing strategy. This vision paper outlines instrumentation platforms for point, plot, reach, and hillslope scales that could be located within the "characteristic" landscapes of river basins. The network of observing platforms then forms the basis of a "Hydro-Mesonet" that can potentially support multiscale, multiprocess scientific studies necessary to understand and improve forecasts of our water resources at the river basin scale. This paper concludes with a discussion of how a network of such sites can support research at the level of the individual researcher and scale to the level of community-wide initiatives.

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1. Introduction

[2] River basins in the eastern United States, such as the Susquehanna River Basin, have a well-documented history of resource use, land development, economic challenges and evolving population patterns [*Stranahan*, 1995]. The evolution of this regional landscape in unison with human activities over the last 400 years, has altered the quantity, quality, and regimen of water and ecological resources of the region [*Goetz et al.*, 2004]. Over this same period, the global climate system has interacted with the regional terrestrial hydrology in important yet unquantified ways (e.g., hurricane and snowmelt flooding, persistent droughts, stream sedimentation, and nutrient loading). The region's water resources will continue to be shaped by human development and climate change, motivating the need to elucidate the interdependences of the hydrologic, terrestrial, and biochemical processes that will determine the future of the system's freshwater resources.

[3] Globally, we are challenged to determine whether development is unsustainable and to predict the long- and short-term hazards of hydroclimatic variability and change. Like other urbanizing regions, human activities in the Mid-Atlantic have increased atmospheric emissions of green-house gases that may potentially contribute to changes in the region's climate and the energy balance at the Earth's surface, while also altering the function of forests, lakes and rivers of the region. At local to regional scales impacts of storm water from urban/suburban development on water quantity and quality have been a long-standing problem for surface and groundwater resources. Although society has made significant progress toward minimizing the local impacts of development on water resources, assessing the large-scale collective impacts of human activity is difficult to accomplish without integrated assessments at the river basin scale. The science community needs to address how human development and climate change are affecting water resources, specifically, water availability and use, over the natural scales of large river basins [*National Research Council*, 2004]. Scientists also need to develop indicators of the impacts of human development on water resources

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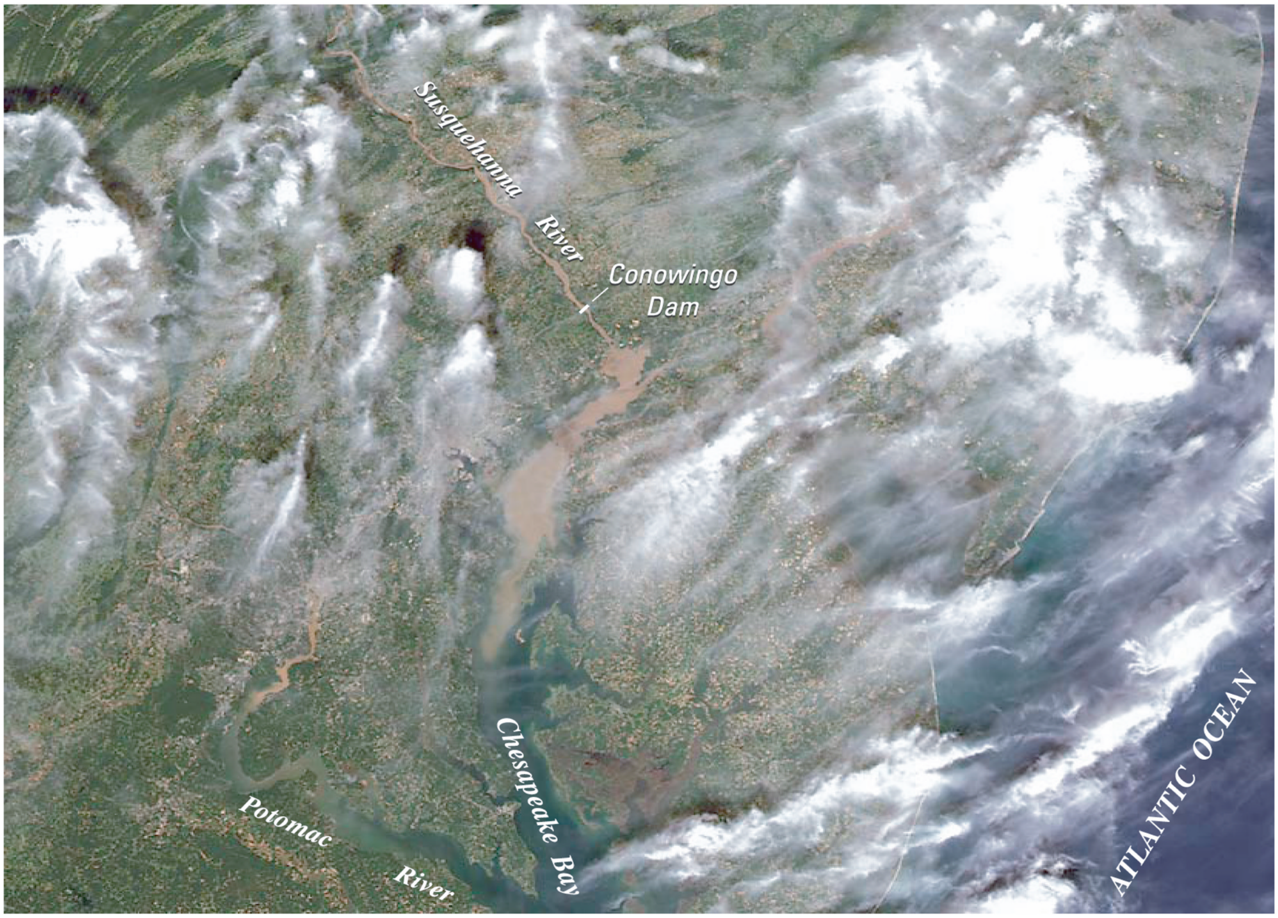

Figure 1. A NASA TERRA satellite photograph adapted from *Gellis et al.* [2005] showing the high suspended-sediment concentrations within the Chesapeake Bay Watershed caused by Hurricane Ivan on 21 September 2004. The turbid waters of the Susquehanna recorded a suspended-sediment concentration of 3685 mg/L at Conowingo dam, Maryland [*Gellis et al.*, 2005].

and to monitor, assess, and quantify our progress toward achieving sustainability.

2. Why River Basins Should Be Observed

[4] The imprint of human activities, climate variability, and climate change on the terrestrial hydrologic system is accelerating (AGU Council, 2003, Human impacts on climate, http://www.agu.org/sci_soc/policy/climate_change_position.html), and the pace of change makes it necessary to reconsider the scientific basis of our current water resources management strategies. This will require a long-term commitment to advancing basin-scale observation and science. Basin-scale hydrologic experimentation will improve our ability to observe and predict the responses of large river basins to hydroclimatic and anthropogenic change. River basins, as the organizing units of terrestrial hydrology [*Gupta et al.*, 2000], evolve from local, regional, and global interactions within the human-climate-terrestrial systems. Figures 1 and 2 adapted from *Gellis et al.* [2005] present a visually striking example of how the components of the human-climate-terrestrial system are inalterably linked. These images show the regional effects of the turbid sediments generated by Hurricane Ivan on the Susquehanna River and the Chesapeake Bay. The images demonstrate that understanding and managing the impacts of hydroclimatic and anthropogenic change will require basin-scale experimentation and modeling strategies.

[5] Our ability to predict long-term hydrologic response to climatic, land use, and land cover changes at the basin scale is limited by the significant uncertainty associated with the paths and residence times of water within the tributary watersheds that compose river basins. Most hydrologic models only represent the pressure gradients within water resources systems and do not attempt to represent flow paths or residence times explicitly [*Brandes et al.*, 1998; *Duffy and Cusumano*, 1998; *Weiler et al.*, 2003]. Reproducing the main system modes with respect to the pressure response can often be achieved with very parsimonious models [*Young*, 2001], but new modeling approaches are required to advance our understanding of surface-atmosphere-groundwater interactions as well as solute transport.

[6] Advancing our understanding of flow paths and residence times will require basin-scale observations that will lead to improved conceptual models of the geometrical, material, and forcing frameworks necessary for simulating human and climate impacts on river systems. Moreover, improving our conceptual understanding of river basins will require documentation of water use, point source wastewa-

Figure 2. Release of water from the Conowingo dam on the Susquehanna River in Maryland on 21 September 2004 after Hurricane Ivan on 17–18 September 2004. The discharge is 384,000 cubic feet per second. This figure and the supporting data were adapted from *Gellis et al.* [2005]. The photo is courtesy of W. McPherson, USGS.

ter discharges, water withdrawals, interbasin water transfers, land use and land cover affecting nonpoint source pollution, storm water storage and recharge facilities, surface reservoir developments, aquifer storage and recovery projects, and the water policies implemented within each watershed planning unit [*National Research Council*, 2001b, 2004].

[7] The river basin provides a natural scale for designing observatories that work in parallel with operational monitoring efforts (such as the water quantity and quality networks of the U.S. Geological Survey) to characterize the quantity and quality of atmospheric, surface, and subsurface waters over large, mixed land use watersheds. Observation at the basin scale will allow scientists to assess the cumulative impacts of human interventions and climate variability/change. Prior studies [*Langbein*, 1979; *Moss*, 1979a] have noted that while operational monitoring initiatives provide important data resources, they rarely are designed for scientific purposes. River basin-scale observatories offer an opportunity to adaptively design observation networks that can augment operational monitoring networks and provide coherent strategies for scientific experimentation.

3. Human System Impacts of Land Use and Land Cover Change

[8] Urbanization, land use, and vegetation changes within a river basin shift pathways and water budgets of the hydrologic system. For urbanization and land use, these changes are generally in the direction of decreasing subsurface flows and increasing surface flows [*DeWalle et al.*, 2000; *Dow and DeWalle*, 2000]. Storm water management seeks to reverse that trend by promoting greater infiltration and groundwater recharge. Urbanization changes flow timing and increases peak flows at the mesoscale. New technologies for storm water management such as low-impact development in the Mid-Atlantic region [e.g., *U.S. Department of Housing and Urban Development*, 2003] have emphasized reducing volumes of storm water generated by increasing groundwater recharge on the development site. Alternately, land cover changes from land development may aggravate low-flow and drought conditions, as increased groundwater withdrawals for residential, industrial, and commercial use reduces baseflow to streams and springs. Urbanization and the concomitant shift in vegetation and changes in infiltration, alters flow paths within watersheds. Hydrologic measurements alone may not be sufficient to quantify this impact, and environmental tracers and stable isotopes of hydrogen and oxygen might be useful tools to support hydrologic change detection, especially characterization of mean residence times of subsurface waters [*DeWalle et al.*, 1997; *McGuire et al.*, 2005]. A deeper physical and predictive understanding is necessary for assessing flow regimes across large basins in response to changing land use practices.

[9] Trends in water quality related to human activity include the combined effects of point source and nonpoint source pollutants from agriculture, urbanization, and atmospheric deposition. The effects of human influence must be viewed at a regional scale, given the large scale and the degree of connection between urbanization, agriculture, and industry within the river basin. The U.S. Environmental Protection Agency (USEPA) is currently using total maxi-

mum daily loads (TMDLs) regulations to help mitigate point and nonpoint source pollution in watersheds [*National Research Council*, 2001a]. TMDLs are set as the maximum amount of various pollutants that a water body can assimilate without violating water quality standards. The USEPA is proposing that best management practices for storm water and other nonpoint sources be used in combination with National Pollutant Discharge Elimination System (NPDES) permits for point sources to achieve TMDLs in the context of overall watershed management plans involving public input to control pollution. In regions with a large range in land use types such as the Mid-Atlantic, identifying the respective sources of nitrogen and phosphorous pollution in water bodies remains a major challenge and limitation for TMDLs.

[10] Within the urbanizing watershed, policies and actions related to water supply development, wastewater treatment, storm water management, wastewater recycling, and land use and land cover changes will have a profound effect on water quantity and quality [*National Research Council*, 2001c, 2004]. Understanding how policies related to water management are adopted and implemented at the grass roots level is critical to projecting future trends. For example, in Pennsylvania where planning is practiced at the township level, numerous different approaches and stages of implementation to storm water management are currently underway in townships within the same watershed. Only by careful documentation of changes in storm water management policy and implementation can the proper interpretation be given to future hydrologic data trends on these watersheds. Consequently, understanding coupled human-watershed dynamics also demands socioeconomic monitoring [*Hisschemoeller et al.*, 2001; *Van Asselt and Rotmans*, 2002] for scientific synthesis and understanding.

4. Climate System: Effects of Climate Change

[11] Quantification of possible climate change and climate variability effects on the hydrologic regimes represents our second major challenge in this vision. Current climate predictions lack hard information on the role of terrestrial hydroclimatic response and feedback [*U.S. Global Change Research Program* (*USGCRP*), 2003]. An observational network of soil moisture, evapotranspiration, groundwater, and lateral water fluxes (surface and subsurface) that is on par with the network of precipitation and stream gages should improve our overall understanding of the total movement of water in the Earth system. For example, fluxes of pollutants from the atmosphere may be affected by the combined effects of temperature and precipitation changes predicted for the Mid-Atlantic region [*Buda and DeWalle*, 2002]. Even if an extensive hydrologic network is built, however, hydrologists are faced with the problem of forecasting hydrologic regimes and shifts that have not been previously observed.

[12] One consensus view is that climate models provide "credible" simulations of the current climate, at least down to subcontinental scales and over temporal scales from seasonal to decadal [*McAvaney et al.*, 2001]. The projected magnitude of future climate change, as characterized by the increase in global mean temperature over the next 100 years for a CO_2 increase of 1% per year, varies by a factor of 3 among models [*Cubasch et al.*, 2001]. The pattern of the projected climate change on continental scales is generally consistent among models [*Cubasch et al.*, 2001; *Giorigi et al.*, 2001]: the troposphere warms, with greater warming at high latitudes, over land and during the winter; Northern Hemisphere snow cover decreases; evaporation increases; precipitation increases in the tropics and high latitudes and decreases in the subtropics; midcontinental soil moisture decreases in the summer; interannual variability in Northern Hemisphere summer monsoon precipitation increases; and intensity of rainfall events increases.

[13] In a synthesis of many such studies of streamflow trends, *Arnell et al.* [2001] note that streamflow has changed in a manner that is largely consistent with precipitation. Globally, precipitation over land appears to have increased by 2% over the past 100 years, with much greater increases in middle and high latitudes of the Northern Hemisphere and decreases in the tropics and subtropics of both hemispheres. Another trend has been a shift in flow from spring to winter in many watersheds in middle and high latitudes, which is largely consistent with increasing temperature, decreasing length of winter, and decreasing snowpack [*Westmacott and Burn*, 1997; *Cayan et al.*, 2001; *Huntington et al.*, 2004]. Projections of mean temperature for the end of the 21st century exceed the range of current interannual variability in many regions. For example, in the Susquehanna River Basin, projected temperature increases for 2100 are from 2 to 4°C whereas past interannual variability is less than 0.5°C [*Najjar*, 1999]. On the basis of the limited hydrologic record to date, hydrologists do not have the data to evaluate how hydrological systems respond to temperature changes of this magnitude.

[14] Two steps should be taken by the hydrologic community to enable future hydrologists to quantify the response of water fluxes and reservoirs to climate change. Foremost among these is "observation." Because vegetation influences many water fluxes, it is imperative that these observations allow scientists to quantify ecosystem responses to climate change. For example, ecologists need to know the direct response of forest ecosystems to increases in temperature and CO_2. Because the expected decadal and centennial timescale of the anthropogenic climate change is similar to that of forest turnover, it is essential to capture transient responses of ecosystems. Hydrological monitoring should include indicators of ecosystem function, such as primary production, respiration, speciation, and age distribution. These needs are similar to programs that are currently monitoring the terrestrial carbon cycle [e.g., *Birdsey and Heath*, 2001; *Billesbach et al.*, 2004]. For instance, Ameriflux is a network of towers that measures fluxes of carbon dioxide, water vapor, and sensible heat between the land surface and the atmosphere. Section 6 proposes instrumentation array platforms that could allow hydrologists to build on the existing capabilities of the Ameriflux program and extract maximum information about hydrological processes in cost effective ways.

[15] Paleohydrologic reconstruction is the second step needed to project future hydrologic responses to climate change. In the context of observatory design, paleohydrologic reconstruction can provide insights into long-term trends within hydrologic systems and guide the development of sampling strategies capable of detecting their signals. This field, although still in its infancy, furnishes a

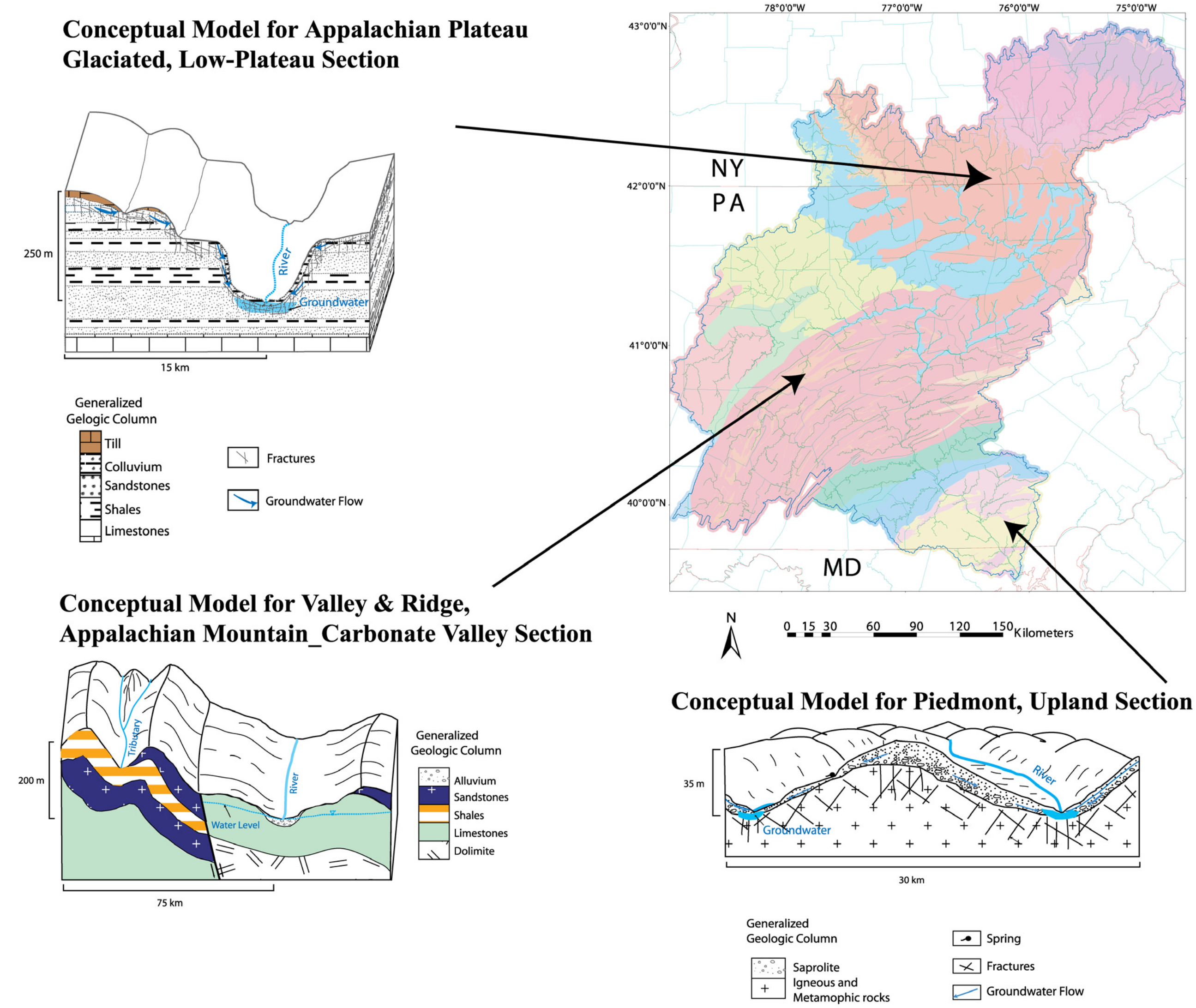

Figure 3. Susquehanna River Basin spans multiple hydrological similar regions [*SRBHOS Partners*, 2004].

window into potential future hydroclimatic regimes not observed during the period of record. *Cronin et al.* [2000], for example, developed proxies of salinity from Chesapeake Bay sediment cores to show that "mega-droughts" have occurred during the past 1000 years in the Mid-Atlantic region. Tree rings and lacustrine sediment cores have produced similar findings. Although climate change is extremely difficult to characterize statistically [*Lettenmaier and Burges*, 1978], paleoclimate modeling studies have resulted in improved parameterizations of feedbacks between the atmosphere and vegetation [*McAvaney et al.*, 2001] and demonstrate the potential benefit of utilizing hydrologic reconstruction efforts to advance hydrologic modeling.

5. Building an Integrated Basin-Scale Conceptual Model

[16] Initial observatory planning efforts have focused on basins that are 10,000 km^2 or greater in scale because 10,000 km^2 has been proposed as ". . ..the minimum spatial scale at which the structure of mesoscale meteorological systems can be captured [*Neuse Prototype Hydrologic Observatory Design Team*, 2004, p. 2]. From an experimental point of view, this poses a daunting challenge for a hydrologic observatory that must be addressed through careful conceptual modeling and long-term infrastructure investments that support adaptive observation network design (see section 6.5). Large river basins span a full spectrum of landform, hydrologic, and ecological conditions that require our predictive understanding if the experiment is to be successful. We propose the use of hydrologic similarity regions (HSRs)" to develop an initial understanding of a river basin's spatial and temporal scales for climate, human impact, and terrestrial hydrology to serve as a basis for initial observation network design.

[17] HSRs are land areas with commonality in soils, topography, geology, climate, hydrology and vegetation. An HSR can span multiple watersheds and other natural regions. Figure 3 illustrates that large Mid-Atlantic river basins, like the Susquehanna River Basin, are composed of multiple hydrologic similarity regions. At the first level of

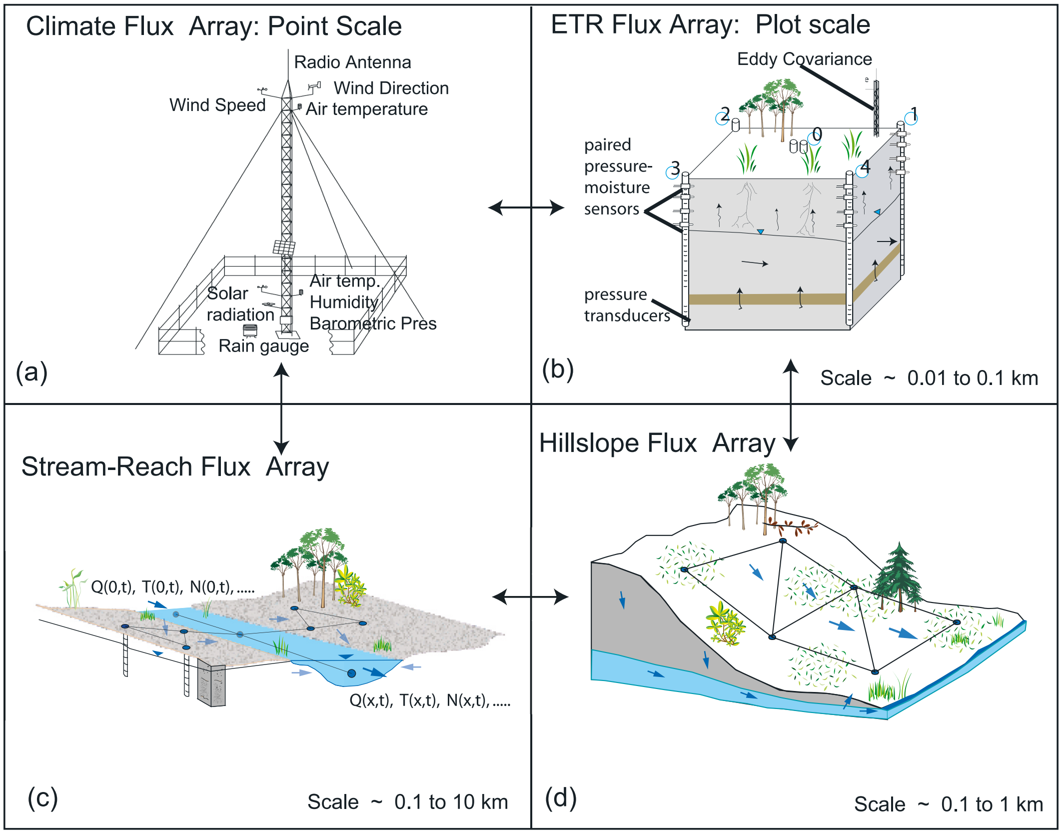

Figure 4. Observing platforms at the point, plot, hillslope and river reach scales. Each platform is to be designed (e.g., length, distance, volume scales) to assure instrument detection limits are sufficient to observe gradient flux.

observation network design, integrated observations can be developed within representative HSRs. This local observing network will attempt to link point observations (streamflow, weather stations, etc.) to watershed characteristics. At larger scales, the topology of the river basin network, provides a rational way to link local-scale processes (e.g., soils, vegetation, terrain, climate, and geology) to the partitioning of water, energy, and nutrients fluxes to a more complete picture of the terrestrial water cycle [*Strayer et al.*, 2003]. Thus local similarity provides a first-order and preliminary characterization of structure in the hydrologic, ecological, and land use conditions within a basin, from which hydrologic observatories can initiate long-term adaptive, multiscale observing strategies.

6. Developing a Hydroclimatic Mesonet

[18] Hydrologic observatories should provide a means for studying the impacts and connections between regional-scale land use/land cover changes and global-scale climate variability or change. The environmental network that we envision as part of the hydrologic observatory will include a cross-scale, real-time, automated network for mesoscale observation that collects information on air temperature, relative humidity, wind speed and direction, barometric pressure, rainfall, solar radiation, soil moisture/temperature, groundwater flow, water quality, and air quality. We refer to the system as a Hydroclimatic Mesonet (HCM), which would be developed in basins connected to existing large-scale operational flow gauging and precipitation networks. Building on the successes of programs such as the Global Energy and Water Cycle Experiment (http://www.gewex.org/) hydrologic observatories should be designed in nested "characteristic" watersheds where the flux arrays shown in Figures 4b–4d can be added to a mesoscale network of weather stations to serve as "super" sites where the enhanced set of instrumentation will provide a more complete measurement of water, energy, and mass fluxes. The overall network should evolve adaptively (see section 6.5) using remote sensing and field campaigns to capture events (e.g., rain on snow floods) or to develop new super sites.

6.1. Multiscale, Multiprocess Observation Platforms

[19] A key determinant of the success of hydrologic observatories is the design and long-term deployment of multiscale, multiprocess observation platforms. The sensor platform illustrated in Figure 4b can potentially support concurrent measurement of a full suite of observations/fluxes at the plot scale and which can be extended to a broad range of science questions including water quality, environmental tracers, and sediment. The purpose of concurrent measurements in a coordinated array is to coordinate theory and experimental data in the estimation of the total flux within the volume defined by the array. The proposed strategy of integrated measurements seeks to link theory and experimental observations over four domains: the atmosphere, the soil column, the shallow groundwater, and streams at the reach scale.

[20] It is generally agreed, that the most reliable measurement of evapotranspiration (ET) is the Eddy Covariance Flux method [*MacKay et al.*, 2002; *Baker et al.*, 2003; *Helliker et al.*, 2004]. However, the method has theoretical and experimental complications due to challenges that arise for closing the energy balance in regions of varying canopy height or in complex terrain [*Kanda et al.*, 2004]. The method may also introduce errors under conditions of stable air, when the turbulent exchange theory does not apply [*Kanda et al.*, 2004]. To reduce and/or control these errors, the present platform can extend the control volume through the soil profile by deploying soil moisture/pressure/temperature sensors. The sensor locations (depth and area) are determined by a priori application of the capillary flow equation (Richards' equation) to assure stability of the theory. A discrete version of the theory is used to estimate the upward flux of ET, or to estimate the upward flux of ET at the soil surface, or the downward flux of recharge to the water table. Using above and below ground theories to measure what is presumably the same flux, should lead to improved ET estimates. However, the question of recharge in the balance equations must still be addressed.

[21] Within the same control volume, projected downward to include the shallow groundwater, a piezometer array could be deployed in a finite difference pattern for assessing the dynamic changes in the water table as well as the lateral flow of groundwater. Recall that the water table is the lower boundary condition for the soil column. The dynamics of the water table influence capillary rise, in some cases it may affect hydraulic lift by plants, and responds to infiltration and recharge of snowmelt at the end of the cold season. The piezometer array [see *Weeks and Sorey*, 1973], admits a direct estimation of the flux to/from the water table (e.g., recharge), while accounting for lateral flow or translation of groundwater. The latter being the major component of baseflow to streams in the watershed. Clearly, the limitation of recharge estimation will be a priori estimation of hydraulic conductivity and soil moisture which would have to be estimated from field testing using tension infiltrometer [*Reynolds*, 1993] and peizometer slug tests [*Bouwer*, 1989]. Taken together, the Eddy Flux system, the soil moisture flux array, and the piezometer flux array will allow estimation of all fluxes within the specified volume. An important extension of the flux in northern latitudes will be the cold season processes of snow, ice, and frost. The "total flux array" concept described above can be extended to include cold season processes. In this case we refer to the experimental setup as an evaporation, transpiration, recharge and snowmelt (ETRS) array. Clearly, there are design issues beyond the scope of this document, but conceptually the integration of these sensors will allow a more coherent estimate of water and energy balances at the plot scale as illustrated in Figure 4b.

[22] ETRS flux arrays introduce the first level of sensor "coherence," where the full-met station and/or Eddy flux is augmented with arrays of piezometers, soil moisture/pressure sensors to estimate vertical and horizontal flux at the plot scale (10–100 m). Simultaneous measurement will aid in minimizing the "errors" of each subsystem and potentially allow independent, accurate estimates of transpiration, evaporation, and recharge. The method and experimental design will need to be tested against traditional methods of estimating evapotranspiration and recharge [*Scanlon et al.*, 2002]. Extension of the basic platform to additional processes and larger scales is discussed in the nest section.

6.2. Upscaling the Experiment: The Watershed

[23] The ETRS flux array illustrated in Figure 4b as proposed will attempt to provide data sets which balance water, energy and mass at the plot scale. Additionally, the flux array can potentially (1) serve as a ground validation site for remote sensing studies, (2) help establish new multi-process constitutive relations, (3) aid the assessment of fluid flow and transport in water quality studies, and (4) aid in elucidating how uncertainty will impact observations and predictions of hydrologic states across multiple scales.

[24] Beyond the plot scale, the stream reach and hillslope experiments illustrated in Figures 4c and 4d represent larger-scale processes that encompass the longer timescales necessary for a complete physical description of the watershed. As in the previous example, the ETRS instrumentation should be designed and deployed using a discrete form of the governing hydrodynamic equations. In the case of the stream reach, the St. Venant equations for mass conservation and momentum [*Bras*, 1990, p. 489] is cast as two-point initial boundary value problem for upstream-downstream gage stations [*Georgakakos and Bras*, 1980]. In the "stream reach" experiment shown in Figure 4c ETRS sensor clusters are placed at paired locations along a stream reach to evaluate differential flow, energy and mass changes. The stream reach experiment could also readily admit the inclusion of sediment and water quality samplers at each gage station. The hillslope experiment illustrated in Figure 4d follows the same approach, with soil moisture/pressure sensors within the vadose zone, and piezometers below the water table, all deployed on a regular or irregular grid as desired for the purpose of closing water balances at the hillslope scale. Note that in each example, optimal locations for sensors can be identified by combining a priori field information with inverse models or stochastic uncertainty forecasts to meet experimental objectives (for reviews on network design, see *Rodriguez-Iturbe and Mejia* [1974], *Langbein* [1979], *Sun* [1994], *Herrera de Olivares* [1998], and *Reed et al.* [2000]).

[25] The result of the proposed experimental design is a nested and connected series of specific experiments, all of which can serve to measure the watershed flux from various processes and over relevant watershed length and timescales. For the hillslope and stream reach, soil moisture and water table sensors could be deployed on a "structured" or "unstructured" grid. However, the latter is preferred for purposes of efficient coverage [*Vivoni et al.*, 2004]. The design of the stream reach and hillslope sensor platform will necessarily be a function of the stream network and the adjacent landform. Combining the sensor platforms illustrated in Figures 4a–4d over "characteristic terrain" (as identified using HSRs) will result in a core network of sensors that measure the impact of topography, geology/physiography, ecology, climate, and land use on river basin systems.

6.3. Monitoring Water Quality

[26] A hydrologic observatory must embrace several basic principles when extending the point, plot, hillslope, and stream reach experiments illustrated Figure 4 to include a basin-scale water quality program. First, the fluxes and storage of water in all its forms and locations must be

considered with regard to quality measurements. This includes, precipitation (mainly rain and snow), snowpack, water in the vadose zone and phreatic zone, streams, lakes, and reservoirs. Sampling needed for water stored in each of these forms and locations may require a different approach. Second, water quality must also be broadly conceived to include chemical, physical, biological and radiological quality criteria of importance in the region, which implies that objectives of the sampling program must be clearly defined. Third, the sampling scheme should be designed with a probability-based network so that statistically valid inferences can be made about water quality over space and time within the entire hydrologic observatory. Here the strong linkage between water quality and physiographic conditions and land use practices within a hydrologic observatory must be considered when choosing sampling sites. Finally, the program should be designed to consider the link between hydrologic conditions and water quality so that mass fluxes, the product of volumetric flow rate and concentration, can be computed to study biogeochemical cycling, but also so that the dynamic response of water quality during ''events'' in atmospheric, surface and groundwaters can be documented.

[27] Dynamic response of water quality to hydrologic ''events'' presents a major data collection obstacle. Since water quality criteria often vary nonlinearly with hydrologic conditions, ''real-time'' water quality monitoring may be needed, such that concentrations at peak flow rates in a stream or in an aquifer during peak recharge are known. Ideally, portable water quality monitoring stations could be colocated with other hydrologic instrumentation to sample, analyze, store data and telemeter results for a complete suite of water quality parameters (e.g., all major anions and cations) concurrently with other hydrologic data collection. Such stations are not routinely available and need to be developed and populated. In the interim, the hydrologist needs to resort to a variety of other methods. Probes may be used, with careful field calibration, to monitor quality parameters such as turbidity, pH, specific electrical conductance, dissolved oxygen, chlorophyll a and selected chemical ions or parameters (Cl^-, NO_3, NH_4, TP and TN) that produce a continuous ''real time'' signal that can be recorded, stored and telemetered. Continued development of portable ion probes for real-time monitoring also needs to be encouraged. Other more sophisticated automated analyzers are available or are being developed [*Global Environment Centre*, 2004] and biological methods such as real-time monitoring of clam, daphnia, algae, and fish activity can be used to, at least, detect onset of toxic conditions for security of drinking water supplies [*Vonderhaar et al.*, 2003]. Periodic evaluations of populations of aquatic organisms, such as fish, benthic macroinvertebrates and phytoplankton, can be used to assist with evaluation of general water quality conditions. Correlations between quality criteria of interest and those that are measurable on a real time basis can sometimes be used to reconstruct dynamic behavior, but in many circumstances water samples must be collected and analyzed separately.

6.4. Monitoring Human Interventions

[28] Changes in water availability and water quality over time and space are the result of complex interactions within the coupled climate-human-terrestrial systems that define our water resources [*Hisschemoeller et al.*, 2001; *Van Asselt and Rotmans*, 2002; *National Research Council*, 2004]. Consequently, understanding coupled human-watershed dynamics requires not only hydrologic cycle monitoring, but it is also imperative to include socioeconomic monitoring. Hydrologic observatories offer an opportunity to identify and monitor the legal, institutional, and other human factors that control land uses, industrial processes, and governmental policies and that are crucial to understanding watershed dynamics [*Sivapalan*, 2003; *Wagener et al.*, 2004]. For example, patterns of urban development and storm water management are major controls on water resources [*National Research Council*, 2001b]. In any one place, as population, land use, technology, and regulation change over time, water availability, and water quality also change.

[29] Monitoring watersheds heavily influenced by anthropogenic changes will require documentation of water use, point source wastewater discharges, water withdrawals, interbasin water transfers, land use and land cover affecting nonpoint source pollution, storm water storage and recharge facilities, surface reservoir developments, aquifer storage and recovery projects, and the water policies implemented within each watershed planning unit [*National Research Council*, 2001b, 2004]. A challenge in HO design and operation will be to support researchers in synthesizing and analyzing these factors given the often disparate approaches used by local, state, and federal programs in maintaining this information. Obviously, these factors should be selected based on their relevance to each specific watershed. Population density based upon United States census data is also a key variable that can be used to reconstruct the history of human impacts on many watersheds where other data are lacking [*Stankowski*, 1972; *Dow and DeWalle*, 2000]. Health of aquatic ecosystems can also be periodically assessed using fish and aquatic invertebrate species sampling [*USEPA*, 1989] and/or assessments of the condition of stream channels and shorelines [*U.S. Department of Agriculture*, 1998]. Coupled monitoring of human interventions and water cycle changes over the decadal life span of hydrologic observatories can potentially enhance our ability to predict the impacts of policy change, improve management practices, and enhance our understanding of the causes and impacts of hydrologic extremes [*National Research Council*, 2001b; *USGCRP*, 2003].

6.5. Network Design and Evolution

[30] Adapted from *Dooge* [1986], Figure 5 illustrates the cyclical dependence of scientific innovation, prediction, and engineering control on observation networks. In this vision, we have assumed that hydrologic observatories will have decadal life spans that will require a long-term adaptive observing strategy. As illustrated in Figure 5, it must be recognized that scientific agendas are dynamic and need to reflect emerging knowledge that results from combining new data observations and modeling strategies. Figure 5 motivates the importance of ''optimal'' design of hydrologic observatories for addressing both scientific and engineering concerns. *Moss* [1979a] highlights that the network design problem presents two significant challenges: (1) estimating the value of information prior to observation and (2) adapting observation strategies for future data uses and needs. These challenges motivate the benefit of using a Bayesian adaptive statistical framework for network design

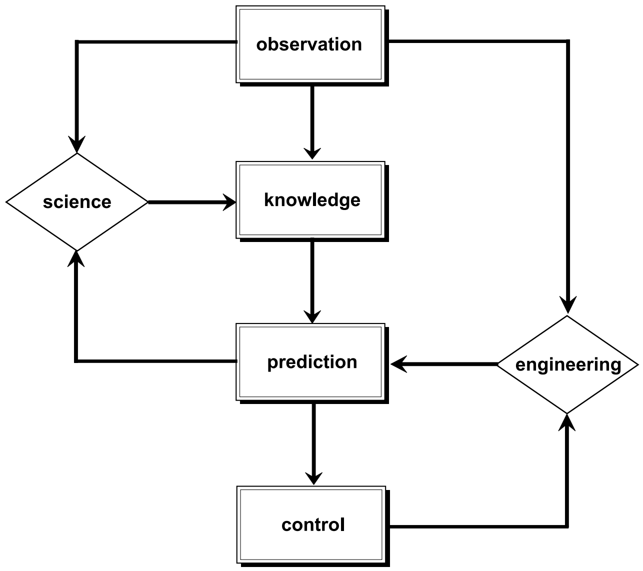

Figure 5. Links between observation, knowledge, prediction, and control (adapted from *Dooge* [1986]).

[*Langbein*, 1979; *Loaiciga et al.*, 1992; *Christakos*, 2000; *Drecourt*, 2003]. Another challenge in the optimal deployment of the multiscale, multiprocess observation platforms proposed in this section lies in defining appropriate criteria for evaluating the quality of alternative observation network designs (e.g., cost, impact on uncertainty, spatial-temporal coverage, reliability, etc.).

[31] The large array of criteria that can be applied in the design of hydrologic observatories reflects that network design is a challenging multiobjective problem as has been widely recognized in the water resources literature [*Langbein*, 1979; *Moss*, 1979b; *Cieniawski et al.*, 1995; *Wagner*, 1995; *Reed and Minsker*, 2004]. Historically, researchers have cautioned that the complexity of the network design problem justifies using informal decision analysis, where expert judgments supported with physical/statistical modeling are used to determine the "optimality" of observation networks [*Rodriguez-Iturbe and Mejia*, 1974; *Langbein*, 1979]. The integrated observation platforms required for hydrologic observatories pose a particularly interesting research challenge because designers will need to consider multiple states correlated in space and time, multiple sensors, as well as site specific hydrologic-ecological-atmospheric information from existing digital resources.

[32] Building on prior hydrologic network research [*Langford and Kapinos*, 1979; *Moss*, 1979a, each hydrologic observatory should have a River-basin Adaptive Modeling and Monitoring Plan (RAMP) in place to provide the organizing principles for guiding the coherent selection and assessment of long-term monitoring sites as well as specialized sites targeted for short-term scientific campaigns. Within the RAMP, the value of new information could be evaluated using simulation models formulated for multiples scales and processes in combination with statistical tools that will be capable of conditioning model-based predictions on observations [*Evensen*, 1994; *Christakos*, 2000; *McLaughlin*, 2002; *Drecourt*, 2003]. In combination, physical and statistical modeling tools will provide a mechanism for sequentially assessing the value added by observables (e.g., changes in system entropy). The RAMP should support the development, testing, and transfer of new modeling and sensing technologies. In this manner, the RAMP represents an evolutionary design paradigm for river basin observation systems that can adapt to new scientific agendas and sensing technologies.

7. Building Community Access and Collaboration

[33] A paradigmatic shift within the hydrologic sciences which embraces cross-disciplinary basin-scale problems should improve our understanding of the atmospheric, land surface, and subsurface processes that characterize river basins from their headwaters to their estuaries or deltas. Advancing this integrated approach to river basin science will require a substantial investment in shared infrastructure and cooperative research, a comprehensive scientific agenda, and a new generation of information and data publication strategies. Fundamentally, the success of any community level observatory network will depend on the hydrologic science community's ability to promote cross-disciplinary collaboration from the level of the individual researchers up to the scale of community-wide initiatives.

[34] Cross-disciplinary, community-wide collaboration can be achieved by explicitly designing the network using the data grid framework [*National Science Foundation Blue Ribbon Advisory Panel on Cyberinfrastructure*, 2003]. The term data grid refers to "...building infrastructure to enhance our capacity to monitor and respond to changes in our environment by developing both the [sensor] networks and the integrated, seamless, and transparent information management system that will collect and stream data... to a variety of end users in real-time" [*Braun et al.*, 2002]. A national data grid for the hydrologic sciences should be established by developing federated networks of real-time sensors and data repositories. A federated sensor and information management architecture will allow researchers to define site specific sensor configurations and data management strategies best suited to local infrastructural constraints and the scale of scientific processes as long as the systems satisfy software and communication protocols defined by the broader hydrologic community.

[35] The protocols will promote multiscale, multiprocess observatories in the sense that climatic, vegetative, topographic, and hydrogeologic elements of characteristic landscapes within river basins can be resolved at the appropriate space-time scales necessary to support specific scientific goals. Federation of sensor communication and software protocols will allow network design teams to collect a core of integrated weather, soil, groundwater, and surface water data in the manner best suited to existing scientific infrastructure within observed watersheds. The initiative to develop hydrologic observatories must provide empirical investigations to define sensor communication protocols and train scientists to utilize state-of-the-art real-time systems that will initiate long-term historical data records for basin-scale processes.

[36] When establishing global network design protocols, the network design experiences of existing large-scale environmental data management and monitoring initiatives should be incorporated (e.g., the NSF-supported Geosciences Network (GEON) http://www.geongrid.org/about.html and the Real-time Observatories, Applications, and Data

Management Network (ROADNet)). ROADNet's real-time data grid protocols [*Braun et al.*, 2002] for autonomous field sensor networks are a generalization of the approaches first successfully employed by the seismic community for building a national network of real-time event detection observatories [*Harvey et al.*, 1998; *A-Amri and Al-Amri*, 2000; *Braun et al.*, 2002]. Effective information and sensor network design protocols will help to guarantee that hydrologic observatories can support individual and community level science.

8. Summary

[37] Hydrologic observatories within large river basins offer the opportunity for scientists to assess climate, terrestrial, and human feedbacks across multiple scales and physiographic conditions to define the roles that terrain, ecology, and geology play in partitioning water, energy, and nutrients across the complex environmental systems that make up river basins. The hydrologic research community has stated that hydrologic observatories will advance the science of river basins in the following areas [see *Neuse Prototype Hydrologic Observatory Design Team*, 2004]: (1) linking hydrologic and biogeochemical cycles, (2) sustainability of water resources, (3) hydrologic and ecosystem interactions, (4) hydrologic extremes, and (5) timescale and pathway of chemical and biological contaminants.

[38] Understanding of the interrelationships among and within these topics requires that three crosscutting themes be included in the design of HOs: (1) forcing, feedbacks and coupling, (2) scaling, and (3) prediction and limits to predictability. A river-basin-scale research strategy will require assessment of climate and terrestrial feedbacks in space and time (including land use change), improving local, regional, and global hydroclimatic predictions, and evaluating how long-term system changes impact stakeholders within a basin's local watersheds. Studying river basin hydrology as a whole system will promote the development of a sound scientific basis for land use planning decisions and the development of hydrologic indicators of sustainable growth, particularly in rapidly urbanizing environments.

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