CUAHSI Hydrologic Information Systems

Project Summary

This proposal will advance integrative hydrologic science through the development of a hydrologic information system that can be implemented at universities throughout the United States. It involves collaboration between hydrologic scientists from the Consortium of Universities for the Advancement of Hydrologic Science, Inc (CUAHSI) and computer scientists from the San Diego Supercomputer Center, and supports a larger strategy at NSF to develop cyberinfrastructure to advance interdisciplinary study of environmental systems. The CUAHSI Hydrologic Information System will be built around a hydrologic data model that synthesizes data from diverse sources describing the water environment, and will support knowledge discovery through its own analysis and visualization tools and links to external modeling and software systems. The Hydrologic Information System will be built as a network so that data sources from many geographic locations can be automatically harvested and imbedded within a common data framework at the user's location. In this project, a prototype system will be developed with the San Diego Supercomputer Center as the hub, and the experience thus gained used to define a request for proposals for a CUAHSI Center for Hydrologic Information which will be responsible for the long-term maintenance and support of this system.

Integrative hydrologic science will be addressed through a series of CUAHSI science driver questions posed first for a hydrologic observatory planning study of the Neuse River Basin, whose data will be synthesized into the CUAHSI hydrologic data model as a prototype Digital Watershed. Similar Digital Watersheds will be constructed using later CUAHSI planning studies for hydrologic observatories elsewhere in the nation, thus providing a comprehensive information base for comparative studies across different hydrologic regimes. These datasets will be made freely available through an internet interface, and the hydrologic data model will also be provided to hydrologic scientists who want to develop Digital Watersheds at other locations.

The intellectual merit of this project is that it harnesses information technology to support hydrologic science by building around a data model that has a coherent intellectual structure and synthesizes data from many disciplines. It will enable the tracing of water movement and transport of constituents vertically between atmosphere, surface water and groundwater, and horizontally through the landscape from watersheds and aquifers to streams, rivers, estuaries and bays. It will integrate data across scales of space and time. This will enable the testing of hypotheses about the interfaces between hydrologic processes in a manner and scale that is rarely attempted now. The results of these studies will be published in journal articles and as a series of CUAHSI monographs. The prototype hydrologic information system developed in this project will be of significant value in itself for hydrologic science research and also as a guide to the future long-term implementation of CUAHSI hydrologic information systems.

The broader impacts of this project include its networking of hydrologic scientists at many universities who will jointly be contributing and receiving hydrologic information. The CUAHSI hydrologic information system and its accompanying datasets will be developed in the public domain and available to the professional hydrology community, and to educators at all levels. As educational exercises using this information are developed by CUAHSI scientists, they will be shared with the broader community through such facilities as the Digital Library for Earth System Education (DLESE).

Results from Prior NSF Support
(only the prior project most relevant to this project is reported)

John J. Helly
Grant # DUE NSDL 01-21584 *($900,381) 10/01-9/03 Bridging the Gap between Libraries and Data Archives*
Summary of Results: This project created a metadata model and a metadata information file format (.mif) for describing earth sciences datasets so that they can be published and electronically archived along with journal articles.
Resulting publications:
Helly, J., H. Staudigel, A. Koppers (2003). "Scalable Models of Data Sharing in the Earth Sciences." Geochemistry, Geophysics, Geoscience, 1010, doi:10.1029/2002GC000318 4(1): 14.
Staudigel, H., J. Helly, et al. (2003). "Electronic data publication in geochemistry." Geochemistry, Geophysics, Geoscience DOI number 10.1029/2002GC000314.
Stephen P. Miller, John Helly, Anthony Koppers, Peter Brueggeman,SIOExplorer: Digital Library Project, Oceans 2001 Conference, Marine Technology Society.

Richard P. Hooper
Grant # *EAR-9796125 ($393,242) 11/99 – 10/03 Hillslope-Riparian zone Reservoir Mixing: A Multi-Catchment Test of a New Methodology for Predicting Stream Chemistry*
J.J. McDonnell, R. Hooper, K. Beven, and C. Kendall
Summary of Results: This project tested the hypothesis that the volume of the riparian aquifer is the first order control on the degree of mixing between hillslope an riparian waters en route to the channel. The study compares and contrasts three basins with different ratios of hillslope-riparian volume at Panola, Sleepers River and Maimai in New Zealand. Preliminary results indicate support for this hypothesis.
Resulting Publications:
Hooper, R.P. (2003) “Diagnostic tools for mixing models of stream water chemistry.” Water Resour. Res. Vol. 39 No. 3 DOI 10.1029/2002WR001528
McGlynn,B., J.J.McDonnell, Stewart, M.,Seibert,J. (2003) “On the relationships between catchment scale and streamwater mean residence time.” Hydrological Processes, 17: 175-181.
McGlynn, B. and J.J. McDonnell (2003). The role of discrete landscape units in controlling catchment dissolved organic carbon dynamics. Water Resources Research, 39(4): 3-1 - 3-18.
McGlynn, B. and J.J. McDonnell (2003). Temporal and spatial sources of small catchment runoff. Water Resources Research, in review.
Tromp Van Meerveld and J.J. McDonnell (2003). Measured non-linearities in subsurface flow: A 147 strom analysis of the Panola hillslope trench. Water Resources Research, in review.
Freer, J., J.J. McDonnell, K. Beven, D. Burns, R. Hooper, B. Aulenbach, C. Kendall and N. Peters (2002). Understanding the spatial and temporal dynamic contributions of subsurface storm runoff at the hillslope scale. Water Resources Research, 38(12): 5-1 - 5-16.
Burns, D., N. Plummer, J.J. McDonnell, E. Busenburg, G. Casile, C. Kendall, R. Hooper, J. Freer, N. Peters, K. Beven and P. Schlosser (2003). The geochemical evolution of riparian groundwater in a forested piedmont catchment. Groundwater, in press

Praveen Kumar
Grant # EAR 97-061211 ($160,000) 9/97 – 8/00 Finding Principles of Large Scale Hydrologic Response: Linking Hydroclimatology and River Basin Dynamics
Summary of Results: This project clarified the role of spatial variability in hydraulic geometry of in dispersion of flow in stream channels, and showed that it is significant when compared to geomorphologic and hydrodynamic dispersion. It was also demonstrated that the entire soil moisture profile not just the near-surface soil moisture plays affects the partitioning of precipitation, and that the temperature anomaly associated with the ENSO cycle penetrates into the deeper soil layers because of the long wavelength of the ENSO signal.
Resulting Publications:
Saco, P. and P. Kumar, Coherent Modes in Multiscale Variability of Streamflow Over the United States, *Water Resources Research*, 36(4), 1049-1068, 2000.

Chen, J., and P. Kumar, Topographic Influence of the Seasonal and Inter-annual Variation of Water and Energy Balance of Basins in North America, *J. of Climate*, 14(5), 1989-2014, 2001.
Chen, J., and P. Kumar, Role of Terrestrial Hydrologic Memory in Modulating ENSO Impacts in North America, *J. of Climate*, 15(24), 3569-3585, 2002.
Saco, P. M., P. Kumar, Kinematic Dispersion in Stream Networks, Part 1: Coupling Hydraulic and Network Geometry, *Water Resources Research*, 38(11), 1244, doi:10.1029/2001WR000695, 2002a.
Saco, P. M., P. Kumar, Kinematic Dispersion in Stream Networks, Part 2: Scale Issues and Self-Similar Network Organization, *Water Resources Research*, 38(11), 1245, doi:10.1029/2001WR000694, 2002b.

David R. Maidment
Grant # OPP-9815808 ($291,744) 3/99 - 8//03 Benthic Community Structure and Biomass in Western Arctic: Linkage to Biological and Physical Properties
Principal Investigators: K.H. Dunton, J.M. Grebmeier, D.R. Maidment,
Summary of Results: This project assembled a digital archive of benthic biomass data in the Western Arctic Ocean collected during ship surveys by various investigators during the past 30 years. Geostatistical mapping of the biomass data identified areas of high biomass concentration in the Bering Strait and mostly lower concentration within the Arctic Ocean. No significant trends in biomass concentration through time could be detected, in part because the surveys did not revisit the same areas repeatedly.
Publications:
Jonsdottir, J.F. and D.R. Maidment, 2000, A GIS Based Analysis of the Benthic Community in the Western Arctic Ocean, CRWR Online Report 00-5, Center for Research in Water Resources University of Texas at Austin
Goodall, J., Spatial and Temporal Trends in the Western Arctic Benthic Community, 2003, MS Report, University of Texas at Austin.

Michael Piasecki does not have prior NSF support

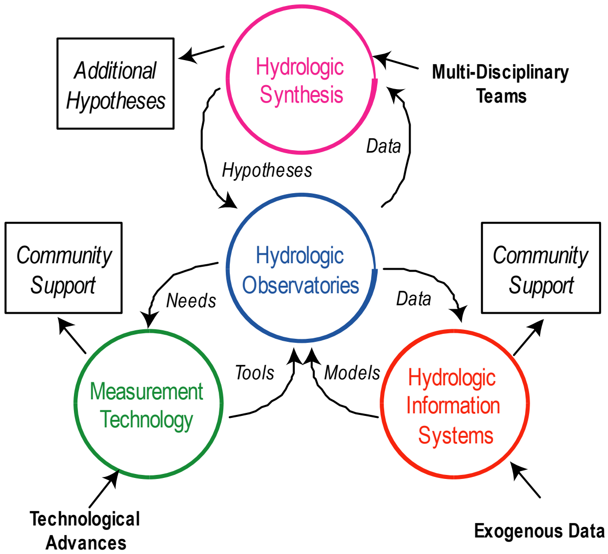
Project Description

Introduction

Water is fundamental to life. The water we drink, the food we eat, the freshwater that sustains plants and animals, the ravages of floods, the dust of droughts—all these have impacted humanity since time immemorial. As economic growth occurs and society increasingly encroaches on the natural world, it is necessary to balance growth with protection of freshwater and ecological systems, and to manage freshwater resources so as to ensure sustainable growth of communities into the future. These increasingly complicated tasks require a deep understanding of freshwater systems because good decisions depend on good science. For example, to achieve the goal of "fishable and swimmable waters" of the 1972 Clean Water Act, non-point sources of pollution must be controlled. Implementing such controls requires understanding the interaction of natural and human sources of pollution in freshwaters, and the combination of atmospheric, surface and subsurface sources of pollution of these waters. This task calls for a much more comprehensive science base for decision-making than was the case when water quality regulation was focused on end-of-pipe controls on wastewater dischargers.

This project will advance integrative hydrologic science through the development of a hydrologic information system that can be implemented at universities throughout the United States.

This system will be based on a hydrologic data model integrating data from many water disciplines, as well as many related disciplines such as ecology and solid earth science, tracing the flow of water and transport of constituents throughout the landscape, and integrating data across a range of scales of space and time. The resulting system will provide an innovative platform for asking an entirely new class of hydrologic science questions concerning the holistic functioning of the hydrologic cycle.



The Consortium of Universities for the Advancement of Hydrologic Science, Inc. (CUAHSI) is an organization currently representing 71 US universities whose goal is to develop infrastructure and services supporting the advancement of hydrologic science at academic institutions. By working collaboratively through CUAHSI, the hydrologic science community can achieve a scale of investment in research infrastructure and accomplish goals that are beyond the reach of individual investigators or laboratories. The CUAHSI vision contains four main research components, as shown at the left: Hydrologic Observatories, Hydrologic Synthesis, Measurement Technology and Hydrologic Information Systems. A coherent, multidisciplinary data framework is required to achieve the integration of these components

Environmental Cyberinfrastructure

This proposal is part of a larger effort at NSF to advance cyberinfrastructure in science and engineering research. Cyberinfrastructure is built on a connected system of computers and information linked through communications technology. As described by the NSF Advisory Panel for Cyberinfrastructure (2003,): "The emerging vision is to use cyberinfrastructure to build more ubiquitous, comprehensive digital environments that become interactive and functionally complete for research communities in terms of people, data, information, tools, and instruments, and that operate at unprecedented levels of computational, storage, and data transfer capacity." This report recommends that NSF establish a new initiative for an Advanced Cyberinfrastructure Program and request $1 billion per year in new funding to support this initiative. The NSF Advisory Committee for Environmental Research and Education (2003) describes an outlook for the first decade of the 21st century that focuses in part on advancing interdisciplinary study of the environment through better measurement and information management: "These new instrumentation, data-handling, and methodological capabilities have expanded the horizons of what we can study and understand about the terrestrial, freshwater, marine, and sedimentary environments, the atmosphere, and near-Earth environments in space". A current NSF Information Technology Research project called GEON, the Geosciences Network, is a collaboration among information technology and earth science researchers to build cyberinfrastructure for the Geosciences. GEON is centered at the San Diego Supercomputer Center. The table below summarizes the functions of some related centers and organizations in environmental and geosciences. There is no existing national center focused on hydrologic information science as is being proposed here.

Hydrologic Science is part of the NSF Geosciences Directorate, and this proposal, like GEON, envisages collaboration between information technology professionals and CUAHSI hydrologic scientists to develop cyberinfrastructure for the hydrologic sciences, using the San Diego Supercomputer Center as a technology partner. By sharing technology development costs with other geoscience communities, CUAHSI will be help to advance the overall goal of environmental cyberinfrastructure while also building its own hydrologic information system. Because water is a common linking element among the atmosphere, oceans and the solid earth, hydrologic science is a good vehicle for advancing interdisciplinary understanding among the geosciences (National Research Council, 2001). Hydrology also has wider links to biological and ecological science and thus is a good vehicle for advancing understanding of environmental systems.

The remainder of this project description is divided into two parts: the first describes what a hydrologic information system is, the second details the implementation plan of how it will be accomplished.

Center	Internet Link	Function
GEON – Geosciences Network	http://www.geongrid.org/	Developing cyberinfrastructure for the geosciences
Chronos	http://www.eas.purdue.edu/chronos/	Integrating stratigraphic databases through time dating
ESIP – Earth Science Information Partners	http://www.esipfed.org/	Regular use of scientifically sound Earth Science information
NEES – Network for Earthquake Engineering Simulation	http://www.eng.nsf.gov/nees/	Integrated experimentation, computation, theory, databases, and simulation of earthquakes
PBI – Partnership for Biodiversity Informatics	http://pbi.ecoinformatics.org/	Synthesis of ecological and biodiversity information
Unidata	http://my.unidata.ucar.edu/	Data access and visualization software, primarily for meteorology
OITI – Ocean Information Technology Infrastructure	http://www.geoprose.com/oiti/	Improve computational and information resources for oceanography
DLESE – Digital Library for Earth System Education	http://www.dlese.org/	A digital library of educational resources to support Earth system science education
NSDL – National Science, Technology, Engineering, and Mathematics Education Digital Library	http://www.ehr.nsf.gov/ehr/due/programs/nsdl/	Multimedia materials in digital form, with users and holdings totally distributed, but managed as a coherent whole.
IRIS – Incorporated Research Institutions for Seismology	http://www.iris.edu/about/iris.htm	Exploring the Earth's interior through the collection and distribution of seismographic data
SAHRA – Sustainability of semi-Arid Hydrology and Riparian Areas	http://www.sahra.arizona.edu/	Integrated, multi-disciplinary understanding of the hydrology of semi-arid regions
NCED – National Center for Earth Dynamics	http://www.nced.umn.edu/	Identify and quantify the major physical, biological and chemical processes that shape the Earth's surface

Hydrologic Information Systems

1. User Needs

It is evident that there is a push throughout science and engineering research to make better use of information technology (NSF Advisory Panel on Cyberinfrastructure, 2003). The Hydrologic Information Systems (HIS) component of CUAHSI is a logical response to meet the specific information technology needs of the hydrology community. A hydrologic information system consists of a hydrologic information database coupled with tools for acquiring data to fill the database and tools for analyzing, visualizing and modeling the data contained within it. No such comprehensive hydrologic information system presently exists, and the central task of the CUAHSI HIS component is to design and develop this system, implement it in universities across the United States, and support hydrologic scientists in its use. To provide coherence within the overall CUAHSI program, the first applications of the CUAHSI HIS will be the regions selected for evaluation as CUAHSI hydrologic observatories. By building a hydrologic data infrastructure for each of these regions by using pre-existing data as well as data that will be collected in the future, a series of "Digital Watersheds" will be created with a capacity to compare conditions in different hydrologic regimes in the nation.

To help decide how a hydrologic information system could best support the hydrologic science community, a survey of the need for hydrologic data, information systems infrastructure, and services was conducted among the participants at the CUAHSI regional workshops in the spring of 2002. The results of this survey (complete responses to which can be viewed on the CUAHSI HIS website, http://www.iihr.uiowa.edu/~cuahsi/his/) reveal a great diversity among hydrologic scientists in the manner in which they use hydrologic information in their research. Nonetheless, some clear common needs are apparent. Among these are:

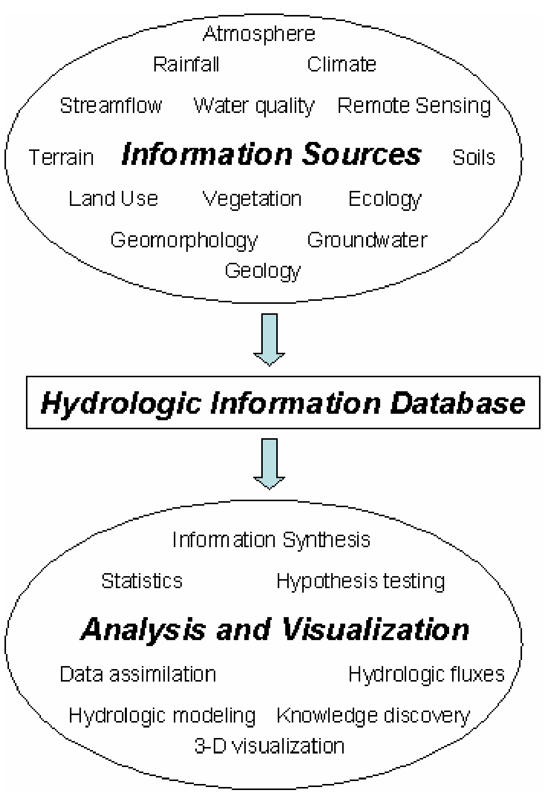
- better access to a large volume and variety of high quality data by means of the internet;
- better access to visualization tools and data analysis software to inspect and assess data; and
- access to standardized datasets for hydrologic fluxes and state variables across the United States that can be used as benchmarks for both individual and community model development.

The CUAHSI HIS will support these needs articulated by the community, as further refined by a more detailed user survey proposed as part of this project. A balance needs to be maintained between the push arising from the advancing capabilities of information technology, and the pull that exists because of the need for information synthesis to support integrative hydrologic science.

2. Hydrologic Information Database

The CUAHSI HIS will consist of three components as shown in the figure on the next page: Information Sources, a Hydrologic Information Database, and an Analysis and Visualization System. The *Information Sources* component comprises all the information that a hydrologist needs to use to describe a Digital Watershed, including atmospheric conditions, rainfall, climate, remote sensing, terrain, land use, geomorphology, streamflow, water quality, ecology, vegetation, soils, geology, and groundwater conditions. The *Hydrologic Information Database* is a repository within which data from the information sources is loaded to describe a particular watershed, and a framework within which benchmark data sets describing particular hydrologic fluxes and state variables are stored. The *Analysis and Visualization* system is used by hydrologic scientists to reduce this vast volume of information to meaningful summaries, to perform statistical analysis and hypothesis testing, to create hydrologic models and assimilate data into them on current and past hydrologic conditions, to quantify hydrologic fluxes, and to support knowledge discovery, data mining and other innovative analysis techniques. The visualization component of this system will produce maps and graphs and other visual products that help hydrologic scientists interpret and understand the results of analysis.

Hydrologic information is routinely collected and provided by federal government agencies, such as the USGS, EPA, NASA, USDA and NWS, and by an array of state and local agencies. Individual hydrologic scientists and hydrologic field campaigns have created data sets for particular subjects and regions of the nation. This collection of hydrologic information sources is too vast to list individually in this proposal.



One of the critical challenges in building the CUAHSI HIS is that the information sources are geographically dispersed, the data comes in many formats, some unfamiliar to hydrologists, and the data files may be huge – the task of assembling, converting and synthesizing this information is so large that perhaps 80% of the effort in a study may be devoted to assembling the data and 20% to analyzing them. Compromises in the quality of the data and analysis frequently are made because the task of doing a better job is daunting to a scientist, and overwhelming to a graduate student. The intent in building the CUAHSI HIS is to simplify and streamline this process so that more emphasis can be placed on analyzing data and testing hypotheses and less on the sheer drudgery of data assembly and organization.

3. Hydrologic Data Model

For the hydrologic information database to function as contemplated, it must be carefully designed. A

Hydrologic data model is an abstract database design developed by using a computer aided software tool which is then physically implemented in whatever database system is being locally employed (Jacobson, et al., 1999). Such systems include relational databases such as MS Access, SQL/Server or Oracle, in Extended Markup Language (XML) format as text files, or in binary files in a UNIX or Linux based file server. All tools developed for data acquisition, analysis, and visualization depend on the way the data is structured in the database. Special interfaces to the database are needed for each information source and analysis task that defines how data is input or acquired from the database. One of the critical early tasks in this project is the design of this data model.

Given the needs of integrative hydrologic science and the nature of the hydrologic data sources listed, a hydrologic data model needs to be able to meet the following needs for integrative hydrologic science:

- Represent hydrologic information in each phase of the hydrologic cycle (atmospheric water, soil water, surface water, groundwater);
- Be capable of tracking the movement of water and the transport of constituents across interfaces between phases of the hydrologic cycle, and accounting for the storage of water and transported constituents in each phase (McKay, 1991)
- Incorporate biological data over various temporal and spatial scales (Eagleson, 2002)
- Allow for the construction of a vertical water balance between atmospheric water, soil and surface water, and groundwater (Wilson and Gallant, 2002; Pinder, 2002)
- Allow for describing the horizontal flow of water through elements of the landscape, such as watershed to stream, to river or lake, to estuary, to bay, and finally to the ocean (Abbott and Minns, 1998; Naiman and Bilby, 1998)
- Be capable of integrating geospatial and temporal information;
- Be able to deal with both continuous and discrete spatial representations of data and of the transformations of data from one spatial framework to another;
- Be able to link data from different spatial scales, such as detailed descriptions of channel morphology on small stream reaches referenced to their correct location within the stream network of the basin (Gupta et al., 1986; Quattrochi and Goodchild, 1997)
- Be able to deal with data of any desired time scale and manipulations to transform data from one time interval to another (e.g. accumulation of daily data to monthly data, monthly data to annual data, etc);
- Support the statistical description of error or uncertainty in the information; and
- Have a metadata component so that the lineage of how the data were produced can be traced.

Although the task of defining a hydrologic data model seems formidable, significant progress has been made on some components of this model (Babovic and Larsen, 1998; Wright and Bartlett, 2000). The many kinds of data stored in a hydrologic information database can be classified into four categories:

- *Monitoring data*, such as that coming from the USGS National Water Information System;
- *Geospatial data*, such as river and stream networks, watershed and aquifer boundaries, soil and land use maps, borehole and gage locations – a data model for this information is presented by Maidment (2002);
- *Gridded space-time data*, including Nexrad radar rainfall maps, grids of weather and climate information, remote sensing images, and terrain maps – these data are normally stored in specially formatted binary file formats such as netCDF (Vieux, 2001).
- *Statistical data*, such as the statistical parameters describing a data set, or the percentile values specifying its cumulative distribution function – these are normally developed using an analysis program such as SAS or S+, but there is utility in having these statistical descriptors attached to the primary data so that the uncertainty and expected range of variability of the data can be quantified (Cressie, 1991; Hosking and Wallis, 1997).

Production of data in other file formats such as spreadsheet, text, Mathematica, and MathCAD needs also to be considered in the data model design. It is evident that there is no single file format or data structure that will satisfy all needs, and mechanisms for converting data between file formats will have to be built or acquired from other data systems.

The Hydrologic data model and the verbal description of its various components are critical elements of the intellectual infrastructure of CUAHSI HIS because they provide the language for describing hydrologic systems, and higher level concepts can be constructed for analyzing such systems once the language for describing the foundation has been established. In particular, it is necessary in data model design to be concerned not just with file formats, data conversions, and the like, but also with understanding how these data are going to fit into an analysis framework and how mathematical models using equations describing physical processes can be constructed to use the data. In other words, a conceptual framework is needed that connects the data describing the hydrologic environment with the physical laws that govern how water moves and its properties change in time and space (Gray et al., 1993). This is a challenging task, but a critical one since it forms the foundation for advancements in hydrologic knowledge built using hydrologic information systems.

Since all the tools that the CUAHSI HIS develops are dependant on the structure of the data that underlies them, the design and implementation of the Hydrologic data model is an important task for CUAHSI HIS that needs to be undertaken in the first year of the proposed project, and will be refined and extended later as needs dictate.

4. Hydrologic Meta-Data

CUAHSI HIS will contain an automated data harvesting system for data derived from diverse geographic sources. For this system to function, each data sources must be sufficiently well described with metadata that a user can identify a data set of interest. Hence, metadata descriptions must contain information that can be queried to answer when the data was collected, by whom, where, spanning what period in time, and a unique descriptor of the data variable. Because data may be edited and changed by the entity that collected it, a versioning system is required to identify such changes to the analyst. Secondly, metadata elements must contain information about how the data is stored, for example in ASCII or binary format (digital), or in paper form, or on tape only, and what storage format has been used (for example HDF, or GRIB, netCDF, etc). Third, metadata must contain information about the purpose for which this data set has been collected to give the user an idea in what context this data set exists. In addition, metadata should provide information about issues such as data quality assurance, calibration values for the measurement device, the sampling interval, zero or reference levels for the data, and pointers that direct the user to additional information about the data set (for example, a report associated with a data collection campaign) and the physical location of the data itself.

Several Metadata standards have been developed during the past few years of which the most important ones are: International Standards Organization Technical Committee 211, 19115 norm, the Dublin Core Metadata Initiative, the Federal Geographic Data Committee, the Global Change Master Directory, and the EOSDIS Core System. Currently, the various metadata standards are converging towards compliance with the ISO 19115 norm. Defining and implementing appropriate meta-data standards is important for CUAHSI HIS development.

5. Hydrologic Observatories

The CUAHSI Science Plan calls for the establishment of hydrologic observatories. The basic tenet of the network is that hydrologic science is observation limited. Major breakthroughs in understanding the processes relevant to many of the critical problems facing water resource managers can be achieved only by obtaining a coherent, multidisciplinary data set at much larger spatial scales and longer temporal scales than are currently available. The network will be designed around a set of specific hypotheses, called ‘program drivers’, that are carefully selected not only to be scientifically compelling in themselves but also, once the data is gathered to test them, will yield a data set that will provide a characterization of the observatory that will be useful for answering a broad range of questions. The drivers are directed towards the interfaces among traditional subdisciplines in hydrology among the atmosphere, land surface, groundwater and surface water, as well at the interfaces between hydrology and closely allied fields such as geology and ecology. Some drivers will be applied to all observatories (and form the basis for the network design); others will be directed towards issues specific to a single basin.

Because observatories of this scale and complexity have never been attempted before, the Neuse Basin in North Carolina, has been chosen by CUAHSI as the site of a hydrologic observatory prototype design. The Neuse Basin has an area of 14,500 km^2 and has been entirely covered with LIDAR terrain mapping as part of North Carolina's flood plain mapping program. The hydrologic cataloging units making up the Neuse basin form part of the South Atlantic Gulf water resource region.

From an informatics perspective, the data sets to be collected by the observatories represent a major challenge. Data will not only be highly dimensional but may be static or dynamic, discrete or continuous in time and space, continuous or categorical in magnitude. Queries must be constructed across such disparate data types, summaries made or values extracted and formatted in a manner conformable with the analyses to be performed.

6. Digital Watersheds

A digital watershed is a hydrologic analysis region for which the CUASHI Hydrologic Information Database has been populated with existing data, which includes both archived information and direct access to real time measurements, such as those made by the USGS, which are formatted according to the requirements of the CUAHSI data model. In this manner, a consistent set of hypothesis tests can be conducted to address the science driver questions for hydrologic regimes of the nation. The general science driver questions, and the Neuse basin-specific questions will be addressed, and means examined to determine how these questions can be answered by using the Digital Watershed. The Neuse Basin Digital Watershed will be published and made freely available for use by researchers located anywhere. It is inevitable that not all the information needed to address these questions will exist – indeed this is the reason for establishing an observatory to measure new information. The data structures needed to acquire, archive and display this new information will be designed as part of the Neuse prototype study.

Following completion of the Neuse basin prototype study, CUAHSI will initiate ten planning grants for developing hydrologic observatories at other locations in the United States having a variety of hydrologic conditions. These may include the snow-fed watersheds of the mountainous west, the arid lands of the southwest, the grassland prairies of the Great Plains, the flat terrain of the Gulf Coast, or the rocky hills of the Northeast. A good test of the validity of a hydrologic data model is to see if it can be applied in all these regions in a consistent manner. Digital Watersheds will be constructed for each of these planning regions as part of this project.

Implementation Plan

1. Overview

The implementation of this project will be managed by CUAHSI (http://www.cuahsi.org), which is a legally incorporated not-for-profit organization with offices in Washington, DC. CUAHSI presently functions with a Board of Directors and a system of committees and a small number of full-time staff. The Board and its Executive Committee establish general policies for the CUAHSI, and the Standing Committee for

Hydrologic Information Systems (SCOHIS) has operated within those policies to define the activities in this proposal. Central to these policies is the idea that all significant long-term components of CUAHSI HIS should be defined by requests for proposals and an open, competitive procurement process for awarding of contracts for the establishment of facilities. The CUAHSI Executive Committee has approved an interim policy for non-competitive awards during the first two years of the activity so that the design and prototyping of the HIS can proceed while the competitive procurement process is being established. Although the HIS is conceived as an ongoing activity, this proposal pertains to a two-year development phase in which design, prototyping, and competition of longer-term facilities will be completed. The SCOHIS and its subcommittees contain members from 12 CUAHSI Member Universities and have spent more than one year developing the concepts contained in this proposal.

The long-term success of this endeavor beyond this initial two-year development phase depends on a fruitful interaction between the information technology professionals, who will create the CUAHSI HIS, and the hydrologic-science community for whom this information system is being created. The subsequent implementation phase, which will likely be developed in five-year intervals, will be focused on a *Center for Hydrologic Information* and a set of *HydroInformatics Thematic Centers*. The Center for Hydrologic Information (CHI) will be a professionally run software engineering and data archiving center, which is owned and operated by CUAHSI. The CHI will be staffed by specialists in computer science and information technology and will be responsible for developing and maintaining the CUAHSI software and data and for supporting hydrologic scientists in the use of the software and data. The HydroInformatics Thematic Centers will be located at academic institutions and staffed by academics and graduate students. They undertake prototype software developments, database compilations and educational activities to support the activity of the CHI. It is intended that collaboration and interchange between the academics in the thematic centers and the professional staff in the CHI will jointly allow the creation of valuable and sustained component of the hydrologic information infrastructure in the United States.

The CHI and the HydroInformatics Thematic Centers will be established by competitive bidding processes developed by CUAHSI. The competition for the CHI and the first round of three thematic centers will take place during Year 2 of this proposal. CUAHSI will then present the selected sites in a new proposal to NSF for long-term funding of hydrologic information science infrastructure.

Each of these activities is now described.

2. Center for Hydrologic Information (CHI)

The CHI will be a physical facility, owned and operated by CUAHSI, and located at or near a major research institution. It will be staffed with computer specialists, scientists and support staff, supported by a bank of data servers and internet interfaces. The CHI will have a management structure that will ensure responsiveness to the needs of the hydrologic science community and appropriate interfaces to government agencies that will provide data needed by CUAHSI programs. The CHI generally will favor the use of public domain software, although proprietary software may be more efficient and cost-effective in some cases. In cases where software needs are so particular to hydrologic needs that they cannot reasonably be met with existing software, the CHI will undertake software development projects.

Technical and logistical support to the user community for accessing hydrologic data will be a vital service of the CHI and will include support for basic functions such as querying and download options as well as support for analysis tool selection, and data quality assurance. In addition, it will permit the user community to participate actively in the generation of new data sets to help the CHI data server to grow and expand its knowledge base. Active participation and inclusion of all users is an important concept that has shown its success in the open source and public domain community.

Experience in large-scale field experiments, e.g. land-atmosphere field campaigns like FIFE (First International Satellite Land Surface Climatology Project Field Experiment) and BOREAS (Boreal Ecosystem-Atmosphere Study), and facilities such the Long Term Ecological Research (LTER) sites, has shown that it is imperative to have an organized entity responsible for setting standards for data quality control, archiving, cataloging, and access. This will be especially important for the CUAHSI network of hydrologic observatories, for which CHI will be the responsible entity for the above functions.

3. HydroInformatics Thematic Centers

The successful long-term development of hydrologic information science requires an interplay between professional information technology development at the CHI and a set of roots within the academic community that drive innovation in the advancement of the hydrologic science using the new information tools and data. Moreover, integrative hydrologic science requires that hydrology not be a world unto itself, but rather be vitally connected to its neighboring sciences. The most direct physical connections are between hydrology and atmospheric science, geological science and ocean science because water flows through all these physical environments and none can be completely understood without considering the effects of the others. There is also an intimate interplay between hydrology, geomorphology and ecology, such that changes in water management policies affect the distribution of river flows which in turn impact sediment transport and channel conditions, all of which affect the life cycle of aquatic species.

HydroInformatics Thematic Centers are intended to be academically based centers which will complement the Center for Hydrologic Information by providing the capacity to link hydrology to its neighboring sciences through shared information frameworks. They will be located in Universities, run by a principal investigator, and supported by graduate students. Actvities at these Centers will include design of interface data models to neighboring sciences, advanced prototyping of software tools, dataset development in required areas, and preparing educational materials that show how the tools and data created through the Center for Hydrologic Information can be applied in a practical way in hydrologic science. Technologies developed by the Thematic Centers will be transferred to the CHI to be enhanced professionally into components of the CUAHSI HIS.

Potential topics for HydroInformatics Thematic Centers include hydroInformatics design, hydrometeorology information, geohydrology information, ecohydrology information, real-time hydrologic information, satellite hydrology information, terrain hydrology information, information uncertainty, and community hydrologic modeling. The specific topics for these Centers and the manner in which they will be competed for will be decided by CUAHSI during the period of this project.

4. The Development Phase: Years 1 and 2

The Development Phase will articulate user requirements and provide a prototype system that mainly uses readily available software and hardware components to keep development costs low while enabling effective characterization of system functions to support a Request for Proposals for the CHI. The subsequent Implementation Phase that will encompass the development of the CHI and the HydroInformatics Thematic Centers will be the topic of a later proposal.

The mission and structure of the Center for Hydrologic Information are described earlier in this proposal. However, the hydrologic science community has little experience in operating and using such a complex facility. Therefore, it is proposed that a temporary facility be established for a period of two years to serve in a prototypical capacity while an actual CHI is scoped out and established. This strategy will permit the hydrologic science community to become familiar with the services that a CHI can offer, and at the same time will aid CUAHSI in ascending the learning curve of operating such a facility.

San Diego Supercomputer Center as a Technology Partner

The San Diego Supercomputer Center (SDSC) will be the technology partner for CUAHSI during the Development Phase and the hub of the prototype hydroinformatics facility will be established there. This center is also the hub for GEON, as described earlier. In this manner, CUAHSI will be able to contribute to a more general cyberinfrastructure development for the Geosciences, and at the same time, CUAHSI will not need to create all the cyberinfrastructure that this proposal envisions, but rather will focus on those aspects of cyberinfrastructure that are particular to the hydrologic science community.

The Development Phase is organized into three major activities:

1. **CHI Procurement**
   This will focus on the development of the Request for Proposals for the CHI the HydroInformatics Thematic Centers and their competitive selection process.
2. **Hydrologic Cyberinfrastructure Development**
   This is comprised of the GEON integration activity and the development of a CHI prototype that will be used to refine requirements for the RFP and provide an optional point-of-departure for the eventual CHI developer.
3. **Information Product development**
   This is a collaborative activity spread across key CUAHSI participants and SDSC for the purpose of producing particular publishable results to inform the RFP process as well as serving as resources for the hydrology community at large.

Research Management

The project activities are divided into tasks, as described subsequently. Each task has a task leader and one or more collaborators. The task leader is responsible for the conduct of the task and the collaborators are included to provide balance between the computer science and hydrologic science aspects – in the event that the task leader is a computer scientist, the collaborators are hydrologic scientists, and vice versa when the task leader is a hydrologic scientist.

The San Diego Supercomputer Center effort led by John Helly is primarily responsible for Tasks 1 and 2 that deal with the CHI Procurement and the Hydrologic CyberInfrastructure development. Dr Helly is presently involved with CUAHSI as the informatics representative on the Neuse Basin Hydrologic Observatory scoping study. Dr Helly will serve as CUAHSI's information technology specialist during the development phase and will collaborate with Dr. Chaitan Baru (Principal Investigator for GEON at SDSC) and Dr Ilya Zavslavsky, to ensure that CUAHSI-related activities are integrated into the cyber-infrastructure development program of GEON.

CUAHSI investigators are primarily responsible for the Information Product Development in Task 3. This is divided into three key tasks corresponding to the three parts of Figure 2, and led by Drs Michael Piasecki, David Maidment, and Praveen Kumar, respectively. The overall project will be coordinated by Dr Richard Hooper, Executive Director of CUAHSI, who will be the primary link to NSF and to the CUAHSI community for the activity, by Dr John Helly representing the SDSC activities and by Dr David Maidment who will lead the academic hydrologic science input to this project. Dr Maidment has served since December 2001 as Chairman of the CUAHSI Standing Committee on Hydrologic Information Systems. Most of the CUAHSI task leaders and collaborators included in this proposal also served as members of this Committee. To provide oversight for CUAHSI on the conduct of this project, this standing committee will be reconstituted with new members not involved in this project, and the project coordinators will periodically report on progress of the research to this committee. Communication with the larger CUAHSI community will occur through two symposia and through cyberseminars scheduled regularly during the project.

Duration and Schedule of Activities

The scheduled start date on this project is September 1, 2003, and the duration is 2 years until August 31, 2005. Since this duration falls over three federal fiscal years, for budgetary purposes, the budget is split into three parts of which the first part will be spent from September through December 2003. The main expenditure of funds will occur in years 2 and 3.

Task 1: Procurement of the Center for Hydrologic Information
Establishing the Center for Hydrologic Information requires a Request for Proposals, which in turn requires an assessment of the functions required at the Center. This task accomplishes those goals.

Task 1.1 User Assessment
Task Leader: John Helly, SDSC
CUAHSI Collaborator: Wendy Graham (Univ. of Florida)
Duration: Month 1 through Month 3
The user assessment is intended to survey the information system needs of the broad CUAHSI community. This survey will be directed and conducted by the SDSC and input will be open to all CUAHSI members. The user requirements development process will solicit user opinions, needs and experiences as well as existing documentation developed by the CUAHSI Executive and efforts such as the Neuse River pilot study. This will be done through personal contacts and a web-based forum for comment and discussion. This information will be developed into an on-line document for peer-review as it develops. This will enable broad participation on a defined schedule so that individuals can elect their own extent and level of participation. As the requirement document nears completion, it will subjected to formally controlled peer-review such that written comments will be individually tracked, recommended responses will be developed by the SDSC team.

Task 1.2 Development of the Requests for Proposals for the CHI
Task Leader: John Helly, SDSC
CUAHSI Collaborators: Rick Hooper (CUAHSI President and Executive Director)
Duration: Month 4 through Month 6
A Request for Proposals for the CHI will be developed to provide an equitable and sufficient basis for the conduct of a competitive proposal process to lead to the selection of the CHI developer by the CUAHSI Executive. This RFP will be modeled after similar centers undertaken by NSF in other domains, such as the IRIS seismology data center in Seattle, and the Unidata center for weather information operated by UCAR in Boulder. The activity of the SDSC team in leading the development of the RFP will not preclude that team from participating in the competition for the eventual CHI should they wish to do so. The selection of the successful bidder will be carried out by a Committee appointed by the CUAHSI Executive whose members will not form part of any of the teams bidding for the Center.

Task 2: Cyberinfrastructure Technology Development

Task 2.1 GEON Integration
Task Leader: Ilya Zaslavsky, SDSC
CUASHI Collaborators: Xu Liang (Univ. of Calif., Berkeley)
Duration: Month 1 through Month 24
This task will support the tracking of GEON developments and the related interoperability requirements and technology transfers that will benefit both GEON and CUAHSI. GEON's infrastructure is built around the Storage Resource Broker, which is a technology developed at SDSC to support data acquisition and sharing on the Grid. The Grid is a network of computers linked by high-speed internet connections, the principal nodes of which are located at the NSF Supercomputer centers at various locations in the United States. The Storage Resource Broker contains a series of data wrappers which enclose files obtained from remote locations with a data description that enables the information contained in those files to be interpreted and integrated even if the formats of the data from the disparate sources are different from one source to another. In this project, data wrappers will be developed for typical hydrologic data sources, including observational data from the hydrologic observatories; water resources monitoring data collected by federal agencies, space-time grids, such as Nexrad radar rainfall and weather and climate information; geospatial information from geographic information systems, and statistical information describing the probability distributions and parameters of variables, and measures of information uncertainty. A CUAHSI hub will be established at SDSC to support CUAHSI-related data queries executed through the Grid using the Storage Resource Broker.

Task 2.2 Pilot HydroInformatics System
Task Leader: John Helly, SDSC

CUAHSI Collaborators: Venkat Lakshmi (Univ. of South Carolina); Kenneth H. Reckhow
Time: Month 1 through Month 24
A pilot system will be developed to further refine the definition of these functional areas for the purpose of a competitive procurement of the CHI. The prototype system will be based on existing relevant methods to be modified as methods and techniques emerge from the Neuse River, GEON and related efforts as well as to accommodate the emergence of a set of data models for sub-disciplines of hydrology. This will provide a sound basis for the exposition, testing and criticism of the pilot as part of the requirements development process.

For example, the prototype data architecture will encompass:

- RDBMS-based Data Models on an application-specific basis
- SRB (storage resource broker) -based client/server network
- Data management and publication model based on the methods developed for the National Science Digital Library
- Metadata catalogue consistent with modern practices and the emergence of the NSDL, GEON and proven methods for navigating data collections.
- Techniques and tools for mobilizing data from each representation to any other within logical, content-specific limits under the supervision of experts in the data domain.

A representative set of prototype thematic centers will also be developed to evaluate the role for integration of scientific research results and data quality assurance processes and procedures. SDSC, alone, does not have all the disciplinary expertise to provide the kind of expert data evaluation and analysis for the wide-range of data sources and products that CHI envisions and requires. This important function, data quality assurance, requires the direct involvement of experts in the various data domains. This is a natural role for domain scientists and hydrology professionals.

The prototype hydroinformatics system will be housed at SDSC with client nodes at appropriate user locations subject to local support capabilities and otherwise web-accessible to any interested CUAHSI participant. Feedback mechanisms for constructive criticism will be provided using methods already usefully demonstrated in the open-source software community projects such as Mozilla, Linux, GMT and similar efforts. These methods include integrated bug-reporting, listservers, and self-identifying beta test participants.

The hardware and software architecture will be open such that the greatest degree of platform independence can be achieved while recognizing the need to accommodate specific dependencies and quirks of critical platforms. The initial intent will be to support Wintel, Linux and OS X architectures with appropriate interoperability interfaces as funding and priority allow.

Task 2.3 Automated Data Harvesting and Digital Libraries

Task Leader: John Helly, SDSC
CUAHSI Collaborators: Yao Liang (Virginia Tech), 1 month Years 2&3
Duration: Months 1 to 18

This will be a CUAHSI research monograph examining alternative data harvesting technologies presently available for assembling data from geographically dispersed internet data sources to a single target location applied to a selected set of the data sources in the hydrologic data inventory. The data harvesting means examined will include:

- Storage Resource Broker from SDSC,
- OpenDap from Unidata,
- Geography Network from ESRI.

The study will include:

- qualitative and quantitative measures of the speed and ease of acquisition of the data,
- assessment of the ability to preview samples of the data before downloading them,

- the capacity of the technology to transform the data from one format to another and to integrate in space and time the data harvested from one source with that from another.

Digital library efforts are well-advanced in other disciplines and are central to the NSF's effort to make research data available to the research community on a broader basis. This task will involve tracking the interoperability interfaces for the DLESE (Digital Library for Earth System Education http://www.dlese.org/) and NSDL (National Science, Technology, Engineering, and Mathematics Education Digital Library http://www.nsdl.nsf.gov/indexl.html) efforts and ensure that the CHI development is consistent with the emergence of standards, conventions and interoperation with these systems. This report will lay out a basis of facts from which the Center for Hydrologic Information will subsequently be able use to build an appropriate automatic data harvesting system for hydrologic data.

Task 3. Information Product Development

Information products will be developed through a combined effort of CUAHSI and SDSC. This task focuses on the hydrologic requirements of the information system. The sub-tasks are arranged in the same order as the flowchart on page 4. Task 3.1 concerns the Data Sources; Task 3.2 designs and populates the Database; and Task 3.3 concerns Analysis and Visualization. Task 3.4 covers the symposia and cyberseminars.

Task 3.1 Inventory and Metadata for Internet Data Sources in Hydrology

Task Leader: Michael Piasecki (Drexel University)
Collaborators: Ilya Zaslavsky (SDSC)
Duration: Month 1 to Month 24
This task will result in a CUAHSI research monograph available in printed and internet form which

- lists the variables describing water and the water environment,
- defines a metadata system which can be used to describe these variables for automated retrieval using the Storage Resource Broker system
- gives URL links to internet data sources describing those variables, and
- contains for each source and variable a summary of the data available at that source,
    - its extent in space and time,
    - the data format,
    - some history of how the data were developed,
    - a short description of how these data can be used in hydrology, and
    - a listing of published studies where this has been done.

Task 3.2 Hydrologic Data Model

Task Leader: David Maidment (Univ. of Texas at Austin)
CUAHSI Collaborators: Winners of the Hydrologic Observatories Planning Grants and members of SCOHIS, Chunmiao Zheng (Univ. of Alabama/Tuscaloosa), LeRoy Poff (Colo. State Univ.)
Duration: Month 1 through Month 24

This will be an intellectual framework for applying informatics to hydrology. It will include:

- Definition of terms for describing the key fluxes and states of hydrologic systems in atmospheric water, surface water and subsurface water,
- A system for flux coupling so that descriptions of individual hydrologic systems can be linked by fluxes defined on their boundaries,
- A set of informatics frameworks or data structures in space and time for describing the water environment and
- Methods for mapping from one framework to another,
- Measures of the uncertainty of data either quantitatively or qualitatively, and
- An analytical basis for connecting the informatics data model with mathematical models describing hydrologic processes.

By the end of Month 6, the hydrologic data model will be published as a CUAHSI research monograph or as paper or a series of papers in a leading hydrologic journal.

After completion in spring 2004, the data model will be populated as a Digital Watershed with data gathered for the prototyping study of the Neuse River, described above. About this time, planning grants will be awarded to 10 additional observatories. This proposal requests funds to support the data needs of these design teams. This support will take the form of populating the data model and the resulting information system with existing data for these studies, which will not only serve to support the studies, but also will provide a robust means of testing the data model and information system. Feedback from these tests will help to enhance both the data model and the information system.

It is anticipated that at least one Digital Watershed will eventually be established in each of the 20 water resource regions of the USA. The populated data model of the Neuse River Basin will serve as the basis of the first of these. Upon completion of the previous phase of the study, all that will be required to enhance the populated data model for the Neuse to the status of a digital watershed is development of an efficient means of remote access to the system. The additional design studies for the observatory network also will be candidates for addition to the Digital Watershed Network, which, if all are in distinct water resources regions, would result in the establishment of the first seven components of this network.

It is proposed herein that the first CUAHSI HIS symposium be held after the first contingent of digital workshops is online. This Symposium will result in a definitive publication on the functioning of the Digital Watersheds, and will set criteria for the design of the remainder of the network. The concepts, procedures, and tools used to develop and operate a Digital Watershed will be made available broadly so that other scientists, who had needs for such a service that were not met by the CUAHSI Digital Watershed Network could establish and operate additional their own.

Task 3.3 Interpretation and Visualization Technology

Task Leader: Praveen Kumar (University of Illinois)
Collaborators: John Helly (SDSC)
Duration: Months 1 to 24
This will result in a CUAHSI research monograph published in printed form and on the internet assessing the various technologies presently available for performing useful tasks on the data once they are assembled at the user's location. It will comprise a listing of the analysis packages that hydrologists would like to use on the data, including:

- hydrologic models,
- statistical packages,
- data assimilation systems,
- data mining and knowledge discovery methods,
- graphing and visualization methods, and tools such as Excel and Mathematica.

Each technology will be summarized and worked examples provided of products that can be generated from it. The data file input and output formats for the technology will be described.

Task 3.4 Hydrologic Information System Symposia and Cyberseminars

Task Leader: David Maidment (Univ. of Texas)
Collaborators: Rick Hooper (CUAHSI Executive Director), David Tarboton (Utah State University) 1 month in Years 2&3.
Duration: Months 1 through 24
An annual CUAHSI symposium on hydrologic information systems will be held in late winter or early spring of each year, and their themes will be consistent with areas of current interest in CUAHSI's overall program. They will also serve as venue to report on the progress of the various thematic centers and as such serve as means to measure the success of the centers.

References

Abbott, M.B., and A.W. Minns, 1998, Computational hydraulics (2nd Ed.), Ashgate Press, Aldershot, 557p.

Babovic, V., and L.C. Larsen, (ed), 1998, Hydroinformatics 98, (2 Vols), Balkema, Rotterdam, 1500p.

Cressie, N., 1991, Statistics for spatial data, Wiley, New York, 900p.

Eagleson, P.S., Ecohydrology, 2002, Darwinian expression of vegetation form and function, Cambridge University Press, 443p.

Gray, W.G., A. Leijnse, R.L. Kollar, C.A. Blain, 1993, Mathematical tools for changing spatial scales in the analysis of physical systems, CRC Press, Boca Raton, FL, 232p.

Gupta, V.K., I. Rodriguez-Iturbe, and E.F. Wood, 1986, Scale problems in hydrology, Reidel Publishing Co., Dordrecht, 246p.

Hosking, J.R.M, and J.R. Wallis, 1997, Regional frequency analysis, Cambridge University Press, 224p.

Jacobson, I., G. Booch and J. Rumbaugh, 1999, The unified software development process, Addison Wesley, 463p.

Maidment, D.R. (ed.), 2002, "Arc Hydro: GIS for Water Resources", ESRI Press, Redlands CA.

McKay, D., 1991, Multimedia Environmental Models, the Fugacity Approach, Lewis Publishers, Boca Raton, Fl, 257p.

Naiman, R.J. and R.E. Bilby, 1998, (ed.) River Ecology and Management, Springer, New York, 705p.

National Research Council, 2001, Basic research opportunities in the earth sciences, Committee on Basic Research Opportunities in the Earth Sciences, National Academy Press, Washington DC, 154p.

NSF Advisory Panel on Cyberinfrastructure, 2003, "Revolutionizing science and engineering through cyberinfrastructure", Report of a Blue Ribbon Advisory Panel, February 3, 2003, National Science Foundation, Arlington VA 22003, p. ES-2.

NSF Advisory Committee on Environmental Research and Education, 2003, "Complex environmental systems: synthesis for earth, life and society in the 21st century", National Science Foundation, http://www.nsf.gov/ere , p.5.

Pinder, G.F., 2002, Groundwater modeling using geographical information systems, Wiley, New York, 231p.

Quattrochi, D.A., and M.F. Goodchild, 1997, Scale and remote sensing in GIS, Lewis Publishers, Boca Raton, Fl,

Vieux, B.E., 2001, Distributed hydrologic modeling using GIS, Kluwer Academic Publishers, Dordrecht, 293p.

Wilson, J.P., and J.C. Gallant, 2000, Terrain analysis, principles and applications, Wiley, New York, 479p.

Wright, D., and D. Bartlett, 2000, Marine and coastal geographical information systems, Taylor and Francis, London, 320p.