

Designing Hydrologic Observatories: A Paper Prototype of the Neuse Watershed

A Report to the Consortium of Universities
for the Advancement of Hydrologic Sciences, Inc.

by

Neuse Prototype Hydrologic Observatory Design Team

CUAHSI Technical Report Number 6

December, 2004

Washington, DC



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for the Advancement of Hydrologic Sciences, Inc.

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Table of Contents

Preface.....	iv
Acknowledgments.....	v
1. Introduction.....	1
1.1 Motivation for Hydrologic Observatories.....	1
1.2 Science Vision.....	2
1.3 Goals of this Document and of the Neuse Prototype Design	3
1.4 References	5
2. Background and Approach	6
2.1 Introduction.....	6
2.2 Understanding fluxes and stores of water, sediment, and nutrients	6
2.3 Spatially and temporally integrated measurements	7
2.4 Spatially stratified measurements for predictive understanding at the river-basin scale	8
2.5 Framework for organization of hydrologic measurements	11
2.6 References	11
3. Watershed Characteristics.....	12
3.1. Topography	12
3.2. Land Use, Land Cover (LULC), LULC change (LULCC).....	13
3.3. Soils.....	14
3.4. Nested watershed sampling design.....	15
3.5 References	17
4. River/Stream Discharge and Overland Flow	18
4.1. River/Stream Discharge	18
4.2. Overland Flow	22
5. Precipitation.....	24
5.1. Key Science Questions	24
5.2. Observing Strategy	24
5.3 References	28
6. Energy Budgets, Evapotranspiration, and Land Surface-Atmosphere Exchange	29
6.1 Land-Atmosphere Exchange	29
6.2 Soil Moisture and Land Surface Processes	31
7. Groundwater.....	34
7.1 Key Science Questions	34
7.2 Observing Strategy	38
7.3 References	39
8. Groundwater Exchange.....	40
8.1 Key Science Questions	40
8.2 Observing Strategy	40
8.3 References	43
9. Water Quality.....	44
9.1 Nitrogen Sources: Key Science Questions.....	44
9.2 Nitrogen Stores: Key Science Questions	48
9.3 Observing Strategy	49
10. Sediment Transport and Geomorphology	52
10.1 Key Science Questions	53
10.2 Observing Strategy	54
11. Social Sciences.....	57
11.1 Key Science Questions	57
11.2 Observing Strategy	58

12. Remote Sensing.....	61
12.1 Key Science Questions	62
12.2 Observing Strategy	62
13. Modeling.....	64
13.1 Key Science Questions	64
13.2 Modeling Strategy	65
13.3 References	66
14. Data Communications	67
15. Operation and Implementation of Hydrologic Observatories	69
15.1 Role of the ODT	69
15.2 Role of Observatory Professional Staff.....	71
15.3 Role of CUAHSI.....	72
15.4 HO Management	72
15.5 Implementation of Hydrologic Observatories	73
APPENDIX A. CAPITAL EQUIPMENT BUDGET ESTIMATE.....	75
4. Stream Gauging and Overland Flow.....	75
5. Precipitation	75
6. Energy Budgets, Evapotranspiration, and Land-Atmosphere Exchange (single site)	77
7. Soil Moisture, Recharge, and Groundwater (single site).....	78
8. Groundwater Exchange with the Neuse Estuary	78
9. Water Quality	79
10. Sediment Transport and Geomorphology	79
11. Social Sciences Survey Data	80
12. Remote Sensing.....	80
13. Modeling.....	81
14. Data Communications	81
Total Capital Equipment Cost Estimate	81
APPENDIX B. HO OPERATIONS BUDGET	82

Preface

The fundamental objective of the Neuse paper prototyping exercise was to provide a proof-of-concept of the scientific and financial feasibility of a hydrologic observatory (HO) on a watershed of at least 10,000 km². In other words, for a watershed of this scale, is it possible to carry out an observing strategy that would provide the basis for addressing critical science questions identified by the hydrologic sciences community, at a reasonable cost?

The Neuse Prototype Hydrologic Observatory Design Team (NDT) was established in early 2003; it was a national committee composed of senior scientists with expertise in the essential subject areas inherent in the science questions to be addressed by a successful HO. Discussions among Larry Band, Marshall Moss, and Ken Reckhow led to the selection and invitation of NDT members. Only a few members of the NDT were familiar with the Neuse Basin, but lack of local knowledge was deemed less important than national involvement and expertise.

The NDT consists of Christopher Duffy (Penn State), Jay Famiglietti (UC Irvine), David Genereux (North Carolina State), John Helly (UC San Diego), Witold Krajewski (Iowa), Diane McKnight (Colorado), Fred Ogden (Connecticut), Kenneth Reckhow (Duke), Bridget Scanlon (Texas), and Leonard Shabman (Resources for the Future).

As originally proposed, the design would focus on a particular “science driver” (e.g., land-surface/atmosphere interactions), and iteratively refine the monitoring design and estimate costs, to address that driver. Once each design and its associated costs were deemed satisfactory, the NDT would sequentially move through the science drivers, refining and augmenting the observation strategy. The final product would be a report on the Neuse HO design that also would include the NDT’s best judgment on the applicability of the design procedures in other hydrologic settings.

The NDT met four times (April, June, August, and November 2003). Prior to and during the

first meeting, the NDT was familiarized with the Neuse basin and with previous and ongoing investigations in the hydrologic sciences in the Neuse. Aside from developing an understanding of the Neuse Basin, the purpose of the first meeting was to agree upon a set of general and Neuse-specific science questions that would serve to launch the design effort.

During and following the first meeting, the NDT proposed an extensive list of science questions, and as these were discussed the group realized that a common set of core data and basic catchment properties emerged as essential for virtually all questions. Accordingly, the design strategy evolved toward a focus on characterizing these properties (e.g., flux, residence time) for water, sediment, nutrients, and other key contaminants.

Frequent interaction occurred between the NDT, the CUAHSI staff (Rick Hooper), Executive Committee (John Wilson), and Standing Committee on Hydrologic Observatories (Larry Band) on the nature and operation of hydrologic observatories. This profoundly affected the NDT’s work, at times giving the impression of a moving target but ultimately leading to a clearer understanding of science and operation at an HO.

The design that emerged and is presented in this report begins with a conceptual model. This is followed by a sequence of science questions or hypotheses; an explanation of the observing strategy follows each question/hypothesis, identifying equipment, sites, measurements, and estimating costs. In some cases (e.g., precipitation, stream gauging), the NDT has been able to address critical issues of scaling and explicit linkage of measurements to science questions. In other cases, this is less evident and must therefore be addressed during the initial years of operation of an HO. In either case, benchmarking of progress and the Hydrologic Observatory evaluation criteria necessitates a quantitative and scientifically defensible strategy connecting observations to basic properties of the catchment and to the science questions.

1. Introduction

1.1 Motivation for Hydrologic Observatories

Freshwater resources have become the strategic resource that constrains future development in many regions in the US and abroad and influences international relations around the world. As has been emphasized in numerous recent reports, our current predictive scientific understanding of the terrestrial water budget, which determines the availability of freshwater resources, is inadequate to support the management of this strategic resource in a changing world. Among the several critical changes needed to address critical regional/national water science and policy issues in the U.S. now and in the future, we must advance the conceptual framework and the research infrastructure for fundamental studies of the terrestrial water budget. **“What is needed for understanding water resources is a more holistic conceptual framework that encompasses regional scale hydrologic systems, land-atmosphere interactions, and the biogeochemical cycles that control contaminant transport”** stated the NRC Water Science and Technology Board in *Envisioning the Agenda for Water Resources Research in the Twenty-first Century* (NRC 2001). The proposed hydrologic observatories are intended to fill this need.

Other distinguished panels within the hydrologic sciences community have arrived at similar conclusions from different perspectives and scientific agendas. Of recent note, the *Water Cycle Study Group of the U.S. Global Change Research Program* issued a report in 2001 with the following recommendation:

“Establish nested basin studies in three to five river systems with varying land cover and levels of human disturbance and regulation...These studies should employ in situ measurements and remote-sensing technologies to characterize and improve understanding of linked water, carbon, and nitrogen transport and transformation processes. (USGCRP-WCSG; Hornberger et al. 2001)”

Why is a large-scale field program of this nature critical? The reductionist approach in hydrology has been successful in developing an

understanding of basic hydrologic processes at small spatial scales. However, the hydrologic community is now moving beyond a focused reductionist approach in order to develop the required holistic conceptual framework. A major impediment to this advancement has been the lack of spatially and temporally integrated, comprehensive hydrologic observations, which can serve as a foundation for understanding hydrologic processes at the river basin scale. For that, we propose a network of hydrologic observatories as a response to these critical science needs.

To function as an effective network, the hydrologic observatories require a consistent set of science topics and cross-cutting themes, which are described below. Furthermore, to address these topics and themes, we have identified core data requirements that define the basic design of each observatory. The measurement approach of the hydrologic observatories will meet three general requirements: 1) **quantitative assessment** of the fluxes and stores of water, sediment, and nutrients, 2) **temporally and spatially integrated** measurements of these fluxes and stores, and 3) acquisition of measurements in **spatially stratified manner that allows for predictive understanding at the river-basin scale**. These design requirements for the core set of measurements for each hydrologic observatory will provide the essential framework within which to overlay studies designed to test specific hypotheses. This attribute of the network will result in synergy well beyond that which could be expected from a set of observatories that are networked only by a protocol of data collection that does not incorporate consistent scientific enquiry. In acknowledgment of substantial past and ongoing field programs, hydrologic observatories must be coordinated with on-going research and monitoring programs to leverage existing investments in hydrologic data. Externally funded grants will support these research studies within the hydrologic observatories. Further, predictive understanding implies an interest in forecasting a response to change, whether it is global change or a local land use decision. Accordingly, each hydrologic observatory, as recommended for the river basin studies proposed by the

USGCRP-WCSG, will ensure that its “research program communicate(s) with local watershed management organizations” (Hornberger et al. 2001) and will result in the ability to synthesize understanding of the underlying science questions at scales much greater than those of the individual observatories.

1.2 Science Vision

A network of hydrologic observatories is proposed by CUAHSI as the core of a suite of interdependent programs (see Figure 1) called HydroView; these programs will collectively advance hydrologic science through innovation in observation and synthesis. The goal of HydroView is to enable Hydrologic Science to predict changes in storages and fluxes of terrestrial waters and associated biogeochemical constituents with greater reliability and lead times. Success requires measurements in addition to those that have been routinely measured, as well as refined concepts, and better predictive models. HydroView begins this process by supplementing current observing systems with an observing strategy that focuses on information at interfaces among terrestrial storages where added coverage is judged likely to bring substantial progress.

Hydrologic observatories will provide the science community with well-supported platforms and

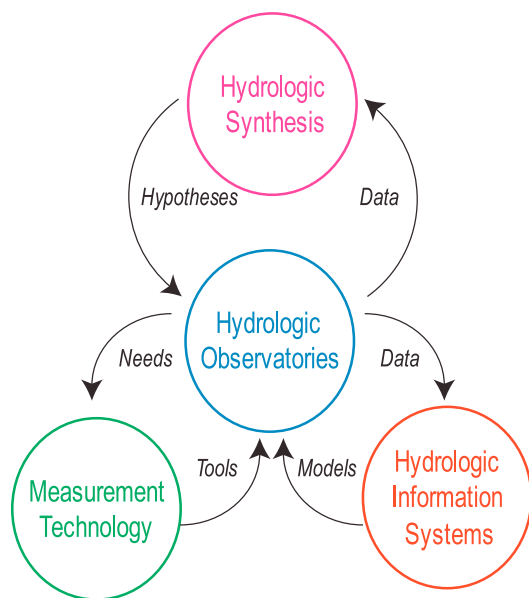


Figure 1-1. Elements of HydroView

infrastructure essential to carry out spatially and temporally nested monitoring and experimental data generation. Each observatory will be a drainage basin of approximately 10,000 sq. km., which is considered the minimum spatial scale at which the structure of mesoscale meteorological systems can be captured. Substantial variations in this design (e.g., the size of river basins, the use of parallel river basins rather than a single basin, the use of groundwater-defined basins, etc.) will be necessary as HOs are implemented over the large variety of landforms in the United States.

The observatory network will be designed to improve predictive understanding in five science topics that were developed through a series of community workshops. These topics are:

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

In addressing these topics, emphasis will be placed on three cross-cutting themes:

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

In the development of specific hypotheses addressing the five science topics, four basic properties of a catchment repeatedly emerged as important. These properties are:

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

These properties refer not just to water (e.g., water residence time within a store, such as the subsurface), but also to sediment, nutrients, and other contaminants. The data necessary for estimation of these basic properties at a range of scales are an essential part of the “core data.”

To emphasize the importance of the basic properties and scaling, we define “core data” more comprehensively than simply the measurements alone. At a hydrologic observatory, core data refers to the monitoring data, the four basic properties listed above, and the conceptual model for scaling. This broad definition means that the concept of core data includes the inferential approaches used (e.g., scaling models) and the key properties derived from the measurements.

For example, if the USGS SPARROW model is to be used to estimate total nitrogen flux at selected locations, the conceptual model leading to the mathematical expressions in SPARROW is a component of core data. This conceptual model represented by SPARROW requires specific measurements of concentration, streamflow, and nitrogen source terms, a model to estimate daily concentration and compute annual nitrogen load, and includes assumptions for first-order loss associated with land-surface characteristics and in-stream processes. As a component of core data, this conceptual/mathematical model indicates how the core measurements are used to estimate basic properties.

The basic design of each observatory will serve as a foundation upon which additional questions of local or regional interest can be explored in a cost effective manner. Given the design concepts and broad science topics described above, an observatory design team’s role is to pick a set of hypotheses of interest to it and to define a data set that will test those hypotheses. If our contention is correct, these hypotheses will require the estimation of the four fundamental catchment properties described above. The observatory design team must articulate how to delineate the basin into stores (e.g., the number of vertical layers, horizontal compartments, etc.), designate which data are required to estimate these properties, and propose an analytical approach to convert the data into estimates of these properties. These data become the core data, which are the community product.

Presumably, these data alone will not be sufficient to test all hypotheses of interest, and additional data will be collected. These additional data are “first publication” data that the investigator retains the right to publish, although they will be released to the public after a specified period. Only the additional data that are not specific to the basic design would be considered first publication data, and, in all likelihood, these data can be collected relatively inexpensively because of the infrastructure that will be in place to support the basic design.

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

The size of a hydrologic observatory should be appropriate for the study of large-scale interactions between the land surface and the atmosphere, as well as for the study of regional recharge of groundwater and other large-scale hydrologic phenomena. Note that these watersheds will be 2-4 orders of magnitude larger than the size of the current LTER sites and probably will contain a wide range of physiographic, geologic, and land-use conditions. Because the intensive study of a drainage basin of this size would be cost prohibitive, a strategy of nesting studies of varying spatial and temporal scales within the observatory will be employed and will be extended into its air shed as required.

1.3 Goals of this Document and of the Neuse Prototype Design

Because observatories at this spatial scale and degree of complexity have never been attempted by hydrologic scientists, CUAHSI supported the development of the prototype design of an observatory in the Neuse River drainage basin to serve as a test of the concept and its feasibility in a real world setting. We believe that this conceptual prototype will clarify the basic design and scope of a typical hydrologic observatory,

and that it yields reliable estimates of the costs of implementing the network of observatories. The prototypical design has been undertaken by a team of scientists from both within and beyond the chosen basin so that a mix of both local and phenomenological knowledge was brought to bear.

As in all valid proof-of-concept studies, there was a likelihood that the concept itself might be proven infeasible on either a technical or a financial basis. However, the CUAHSI community believes that the network of observatories is such an important component of its overall strategy for the advancement of hydrologic science that the expenditure of intellectual and financial capital to conduct a prototype study was the most effective tactic for initiating the observatory program. Furthermore, the conceptual prototype is intended to clarify the basic design and scope of a typical hydrologic observatory, and it yields the first reliable estimates of the costs of implementing the network of observatories.

CUAHSI chose the Neuse Watershed in North Carolina (the watershed of the Neuse River and its estuary) as the site of the prototype design. This basin is well suited for the conceptual design of a hydrologic observatory because of: (1) the

leadership of the North Carolina Water Resources Research Institute (NCWRRI; www.ncsu.edu/WRRI) and the participation of many highly capable scientists from the hydrologic science community in the Research Triangle; (2) the robust suite of both historic and ongoing hydrologic data collection efforts, and (3) the fact that the Neuse Watershed contains a diversity of hydrologic and geographic settings together with a mix of land use that can serve as an adequate test of design feasibility of each of the program drivers.

The Neuse River (see Figure 1-2) originates in the Piedmont, where its drainage is controlled by fractured crystalline rock and flows onto the sandy coastal plain, before reaching its estuary at Pamlico Sound. The drainage area at its mouth (near Piney, NC) is 14,500 sq. km., which exceeds the minimum desirable size (10,000 sq. km) for a hydrologic observatory. The Neuse Watershed is subject to frequent floods and droughts and occasionally is affected by tropical rainfall systems. Groundwater resources are varied because the upper portion of the Neuse in the Piedmont is underlain by crystalline bedrock with locally thick saprolite, while the Coastal Plain is underlain by sedimentary aquifers with a complex stratigraphy derived from the transgressing shoreline.

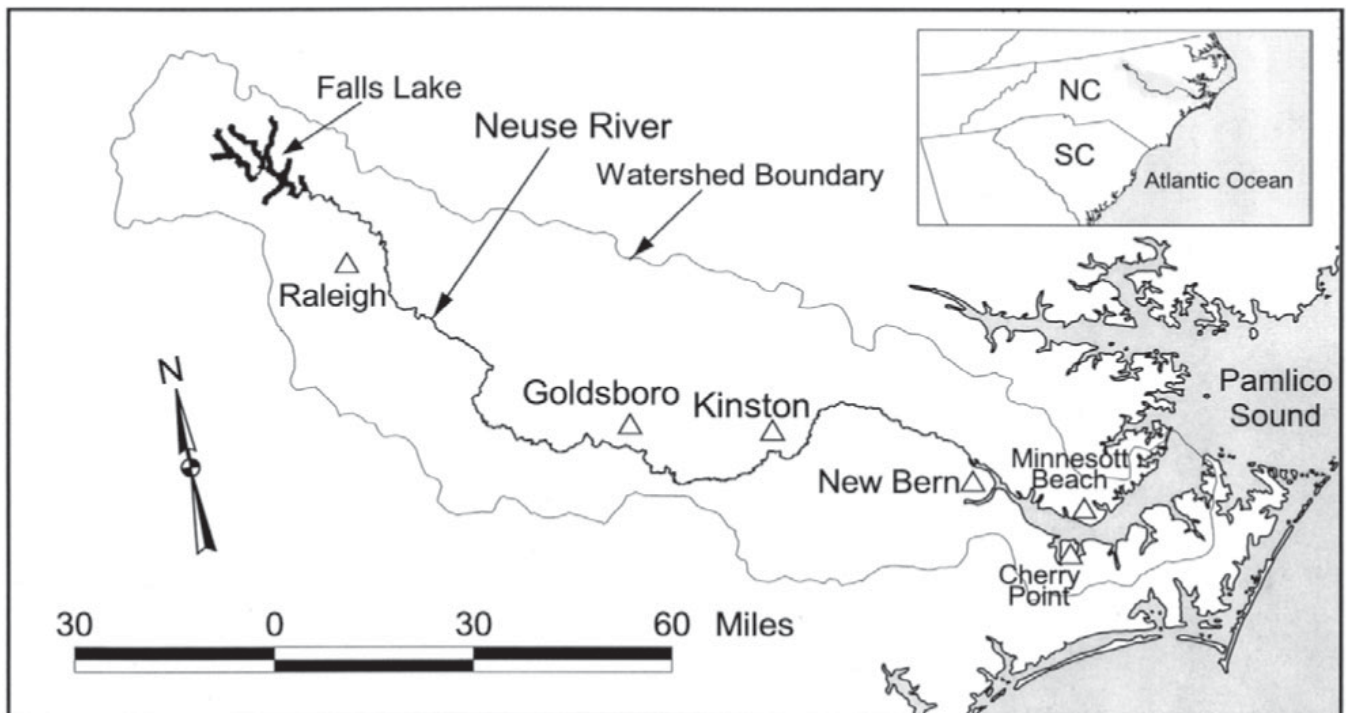


Figure 1-2. Neuse River Basin

The Neuse Watershed includes the rapidly expanding urban area of the Research Triangle amid large areas of agricultural and forest land. Although substantial agricultural abandonment during the 20th Century was accompanied by large-scale afforestation, this trend recently has been reversed with expanding urbanization and a reintensified agricultural sector. Rapid urban growth has resulted in a heterogeneous mix of available water supply, with some rapidly developing communities around Raleigh chronically short of water and with frequent water use restrictions, while other communities have planned adequate resources. The water supply in the Piedmont is from a mix of household and community wells, along with several developed surface water supplies.

The upper portion of the Neuse River drains approximately 7500 km² in the Piedmont and Coastal Plain, including Raleigh and the Research Triangle, one of the most rapidly urbanizing areas of the country. The lower part of the watershed contains major commercial livestock production – largely hog and poultry operations. The shallow groundwater resources of the Coastal Plain are subject to contamination and overuse. Major hydrologic concerns in the basin include: (1) the export of nitrogen into the Neuse estuary and Pamlico Sound leading to eutrophication and fish kills, (2) the vulnerability of water supply given the mix of development, population growth, and recent drought, (3) hurricane-induced inland flooding, (4) and (5) groundwater contamination—particularly in the coastal plain section. Thus, examples of questions central to the design of the Neuse River hydrologic observatory are:

- *What are the primary mechanisms of nitrogen retention in the watershed, and how are these linked to hydrologic processes? How have urbanization in the Piedmont and confined animal feedlot operations in the coastal plain affected nitrogen export, and what has been the effect of this export on aquatic ecosystems?*
- *Are surface and groundwater supplies sustainable in the Neuse Basin given the mix of population*

growth, low and medium density urban sprawl, periodic drought, and potential ground and surface water contamination from urban and agricultural sources?

- *How do hydroclimatic variability and human modifications of the hydrologic system control the dynamics of regional droughts, and what are their ecological and human consequences?*
- *What is the space/time distribution of sediment sources within the watershed at multiple scales? How do urbanization and agricultural operations in the piedmont and coastal plain affect soil loss?*

Guided by the HydroView science vision, and further informed by the compelling hydrologic concerns in the Neuse, the Neuse Prototype Design Committee has developed the design for a hydrologic observatory, with the Neuse Prototype serving as an assessment of the feasibility of the HO concept. The design is presented in the following chapters, beginning with the two background chapters on the approach and watershed characteristics. Building upon the cascading approach to the design, we present in subsequent chapters integrated designs for the diverse processes comprising the hydrology of the basin, followed by integrated designs for water quality, geomorphology, and social sciences. We specifically discuss the use of remote sensing and the role of modeling in the Neuse Prototype. We conclude with a discussion of current perspectives on the operation of hydrologic observatories.

1.4 References

- Hornberger, G. et al. 2001. A Plan for a New Science Initiative on the Global Water Cycle. Water Cycle Study Group of the U.S. Global Change Research Program (USGCRP-WCSG).
- Water Science and Technology Board (NRC). 2001. Envisioning the Agenda for Water Resources Research in the Twenty-first Century. 70 p.

2. Background and Approach

2.1 Introduction

The hydrologic community has made important advances in hydrologic science that support the design of the observatories and meet the three general requirements presented in the Introduction, specifically: 1) quantitative assessment of the fluxes and stores of water, sediment, and nutrients, 2) temporally and spatially integrated measurements of these fluxes and stores, and 3) acquisition of measurements in spatially stratified manner that allows for predictive understanding at the river-basin scale. In this chapter, we review the background understanding for meeting these requirements

2.2 Understanding fluxes and stores of water, sediment, and nutrients

A conceptual model for the storages, flowpaths, and fluxes in the terrestrial

hydrological cycle is required to address the scientific topics of the network. A schematic showing the coupled land, atmosphere, and ocean interactions of such a model, which is appropriate for the scale of the Neuse Watershed or any proposed HO, is shown in Figure 2-1.

Figure 2-1 depicts the spectrum of hydrological processes that are important to characterizing, understanding, and predicting terrestrial water cycling and interactions at the HO scale. For example, precipitation variability is a driving force behind water availability and extreme events such as flooding and drought. Soil moisture in the unsaturated zone is critical in partitioning rainfall into infiltration versus runoff, and solar radiation into evapotranspiration versus sensible heating of the atmosphere. Soil water is also a key component regulating biogeochemical transformations, and the productivity and distribution of vegetation. Further, soil water is a key determinant of groundwater recharge. Evapotranspiration is an essential aspect of surface-atmosphere heat exchange. It also provides moisture to the atmosphere that can subsequently be returned to its basin of origin through the process of precipitation recycling.

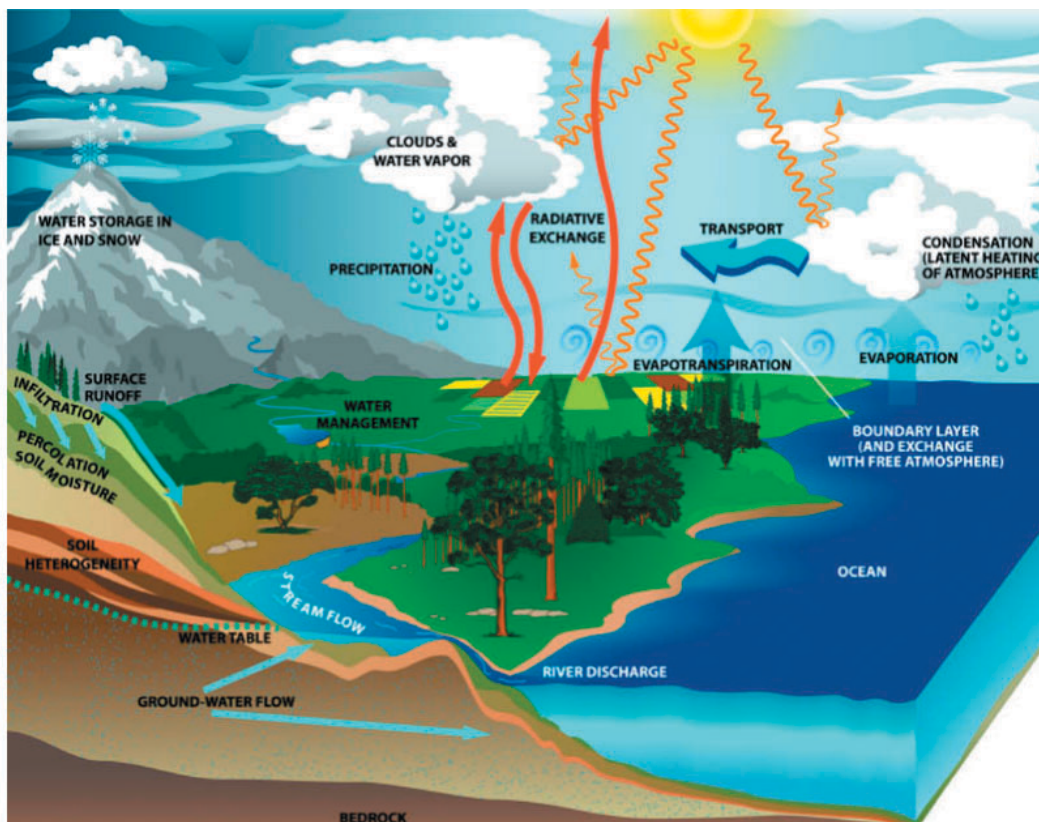


Figure 2-1. Conceptualization of the terrestrial water cycle and its interactions with all other components of the Earth-climate system. [CCSP, 2003]

Surface water and groundwater stores and flowpaths are important supplies for municipal water, and both respond to extreme hydrologic events, and play key roles in transporting sediment and biogeochemical constituents through a basin. Several of these watershed-scale processes impact water quality and related socioeconomic considerations. Clearly then, comprehensive monitoring of the terrestrial hydrology is essential for enhanced understanding and prediction of water cycling on land. Equally important is the development of research infrastructure to develop an understanding of how water mediates the transformation and flux of nutrients, carbon, contaminants and sediments within catchments, across the interfaces between major hydrologic stores (e.g. atmosphere, surface water, vadose and phreatic zones) and into receiving water bodies. An important theme in the design of a sampling strategy is colocated measurements of multi-store and multi-media hydrological processes in order to produce core data to support cross-disciplinary, integrative hydrologic science. At present, no such system currently exists at the basin and cross-network scales proposed by the HOs.

Concomitantly, HO design is confounded by the spatial-temporal scales of variability of the numerous processes and interactions shown in Figure 1, as well as by the varying residence times of the terrestrial water stores. Further, hydrologic processes show considerable interannual variability, and accumulating evidence points strongly to long-term changes in water balance that will be evident and palpable at the HO basin-scale. The impact of land use and land cover change (LULCC) on basin-scale hydrology adds another dimension to this already complex network design challenge.

Here we propose an integrated observing system for terrestrial hydrology in which recognition of varying space-time scales of processes and interactions, as well as of anthropogenic alterations of the water cycle (e.g. through LULCC), is implicit in network design. Important aspects of the design include its measurement of hydrological processes at appropriate space-time scales; integrated sampling of water, chemical and sediment storage, flux and transformation, a framework for scaling point measurements to larger sub-

basin and basin scales based on important land surface heterogeneities; and the ability for cross-network intercomparison with other HOs around the nation. An observing system such as the Neuse River prototype will also form the basis for long-term monitoring, it will provide necessary data and parameters for hydrological and other predictive models, and it will form an important validation site for satellite remote-sensing of water cycle processes (e.g. rainfall, soil moisture, lake and river heights, etc.). It is important to note that remote sensing will comprise an essential component the observing system that will provide a complementary spaceborne, large-scale perspective on basin-scale processes, as well as a critical framework for scaling point measurements to larger basin and regional scales.

2.3 Spatially and temporally integrated measurements

Although the scope of the proposed hydrologic observing system is comprehensive, modern IT infrastructure allows a new level of interoperability, data mining of historical resources, and mediation of disparate data types, resolutions, and formats. Without these advances, the scale of this effort might not be possible. Integrating terrestrial hydrologic information across space, time and process will provide a fundamental advance in data accessibility by data analysts, physical modelers, as well as policy and management investigators.

Furthermore, advancements in hydrologic modeling will allow the coupling of diverse processes in a quantitative and predictive manner in the future. These advances in modeling will be greatly facilitated by the existence of complete and well documented datasets against. Firstly, patterns seen in these datasets will stimulate hydrologists to develop new hypotheses on dominant processes, which can be then incorporated into developing hydrologic models. At the same time, the current models can be evaluated against these detailed datasets and patterns that are not well-represented by the models, and their underlying representation of processes, will be revealed. Finally, the development of new models will inform the evolving design of the HO. In this iterative and synergistic manner, the datasets of the Neuse River HO will stimulate new ideas and development of hydrologic models that can be used in addressing the broad range of water resource challenges that lie ahead in the 21st century.

2.4 Spatially stratified measurements for predictive understanding at the river-basin scale

Our conceptual framework represents the elements of the hydrologic cycle as a spatially distributed set of stores, fluxes, sources and sinks of water and its constituents, including sediment, nutrients, organic matter and contaminants. The next requirement in the observatory design is to organize measurements in a manner that provides a foundation for predictive understanding at the river-basin scale. The critical hydrologic flowpaths within the Neuse River Basin, and other many river-basins, include:

1. topographically driven surface drainage paths
2. subsurface stores (soil and groundwater) and flowpaths
3. the regional stream and river channel network
4. surface water bodies including lakes and the estuary
5. flux across the interfaces between these stores, and between the stores and the atmosphere
6. the activity of human society in directly adding and abstracting water, carbon and nutrients to these stores and flowpaths

While the high resolution DEM and land cover information available in the Neuse will support detailed representation of surface water, sediment and nutrient sources and flowpaths over small catchments, there is considerable uncertainty in scaling a multi-store and pathway response to larger watersheds. An alternative that has been pursued by researchers is to formulate simpler, lower dimensional hydrologic models for “typical” catchment or landscape conditions (e.g. Duffy 1996, Troch et al. 2002, Reggiani and Schellekens 2003). In fact, synthetic unit hydrograph (including the GIUH) methods are simplified runoff response representations for complex surface water responses typical of a given catchment reflecting geomorphic structure, land cover and basin shape and scale. Given the multitude of potential permutations of flowpath networks, land cover and substrate conditions, it is useful to investigate whether a finite set of

“typical” landscape conditions or categories could be found to characterize the heterogeneous hydrologic response of nested, multiscale watersheds.

One strategy for the design of a hydrologic observatory is found in the similarity concept of a “hydrologic landscape”, proposed by many authors, but perhaps best summarized by Winter (2001). This concept provides one example of how an HO network could be designed around a unifying principle that provides guidance for locating measurement sites, scaling up point observations, and a consistent framework for addressing proposed hypotheses. It is not the intention of this section to advocate the use of any particular concept for network design. Rather, one potentially useful example is provided, of which there are many. However, proposers are encouraged to identify a clear framework for scaling local measurements to larger scales.

The concept of hydrologic landscape is based on the idea of local similarity in hydrologic process, where the hydrologic landscape unit is defined as “...an upland adjacent to a lowland separated by a valley side” (Winter, 2001). Figure 2-2 illustrates the concept applied to conditions in the Neuse. We can say that the hydrologic system consists of (1) the movement of surface water, which is controlled by the slopes and permeability

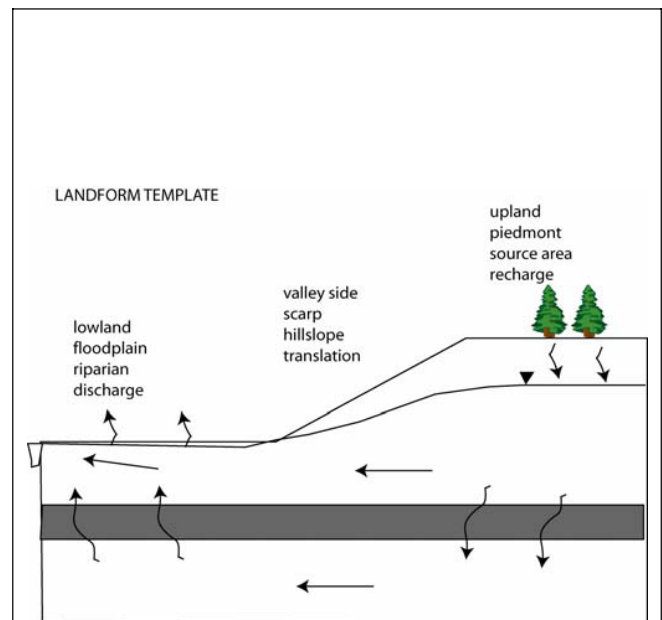


Figure 2-2. The template for a Conceptual Hydrologic Landscape, representing a similarity of scales and processes across the Neuse.

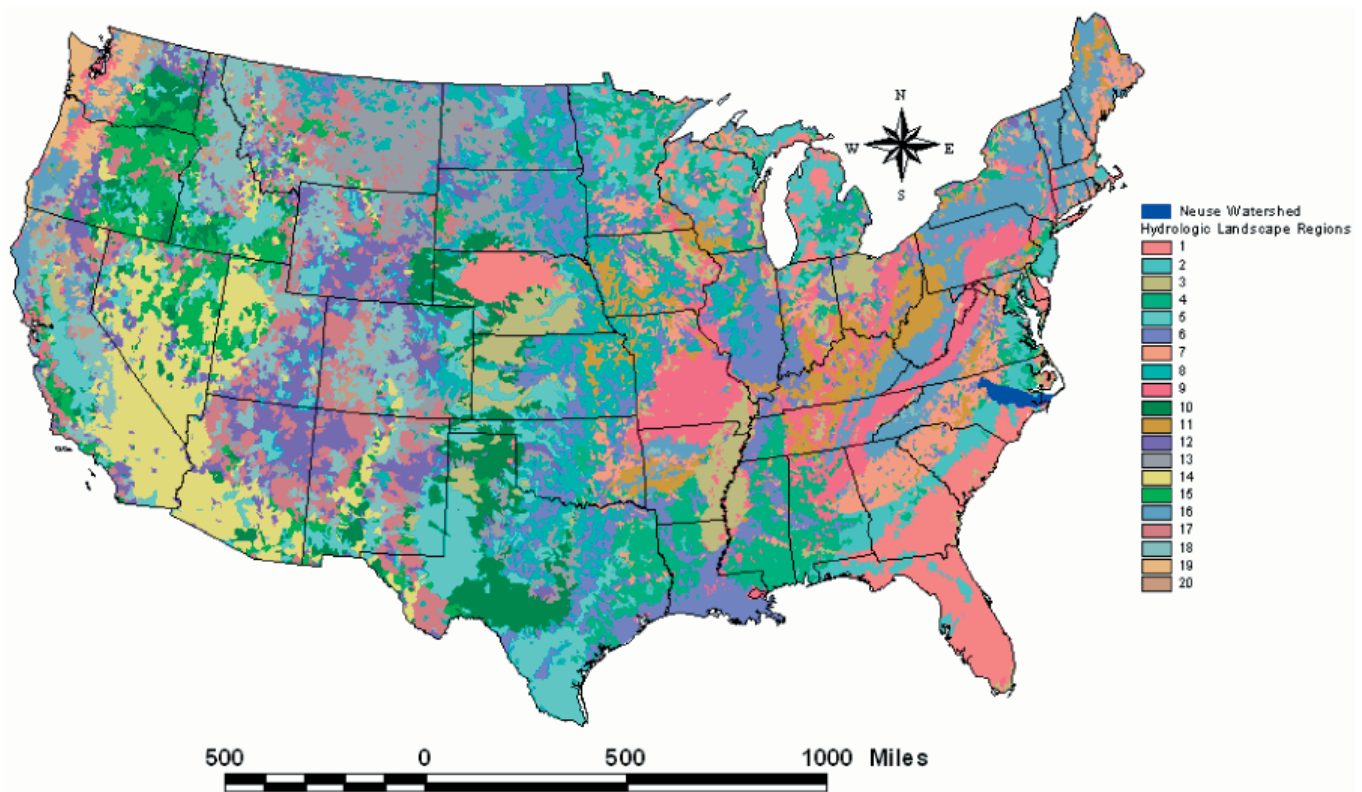


Figure 2-3. Hydrologic Landscapes of the US and USGS
<http://water.usgs.gov/lookup/getspatial?hirus>

of the landscape; (2) the movement of ground water, which is controlled by the hydraulic characteristics of the geologic framework (shallow and deep strata); and (3) atmospheric-soil-vegetation water exchange, which is controlled by climate and surface conditions (Winter, 2001). Each application of the template of Figure 2-2 is meant to be representative of a typical geology, climate, soils, etc. over a specified domain.

The USGS has delineated Hydrologic Landscape Regions (HLRs) across the United States applying geographic information system (GIS) tools and statistical methods including principal components and cluster analyses. The analyses were applied to land-surface form, physical properties (permeability of soil and bedrock), and climate variables that describe the setting of 43,931 small (roughly 200 square kilometers) watersheds in the United States. The analyses then grouped the watersheds into 20

noncontiguous regions (the HLRs) on the basis of similarities in land-surface form, geologic texture, and climate characteristics as shown in Figure 2-3. The HLR dataset contain the following information for each of the 49,931 watersheds across the nation: (1) watershed identification number, (2) land-surface form, geologic texture, and climate characteristics for each watershed, and (3) hydrologic landscape region number for each watershed. (ref. USGS: <http://water.usgs.gov/lookup/getspatial?hirus>)

According to Wolock et al. (2004) all hydrologic landscapes can be conceived of as variations and multiples of fundamental hydrologic landscape units, and these were used to define general landscape types. Wolock et al. have divided the US into some 20 HLR's (hydrologic landscape regions). The original purpose of HLR was to group watersheds in the United States by similarity in landscape and climate characteristics. Table 2-1 illustrates

the type of information contained in the USGS website for each HLR and represents an important source of regional hydrologic data necessary for an integrated design of an observatory. Figure 2-4 illustrates the particular similarity regions for the Neuse Watershed. Clearly the HLR data grid can play an important role in observatory design by creating the physiographic/hydroclimatic template for deploying the components of the observing system.

A central role of the HO network will be to develop and explicitly test strategies for scaling across regions of varying hydroclimate characteristics. Certainly, there are other factors which are not explicitly included in the HLR classification, such as landuse, ecology, transportation systems, and water storage systems. These features of the river basin landscape will require an overlay of additional

geospatial-temporal data fields. For example, ecoregions of North America were delineated by Omernik (1987). One application of this classification was to define areas where conditions affecting stream chemistry were expected to be similar (Omernik and Griffith, 1991). Ecoregion classification will be an important intersection of hydrologic similarity regions captured in the HLR, which will help to identify patterns in ecological processes across the river basin. Similarly, the intersection of other features important to the natural and anthropogenic functioning of the river basin could be accommodated in this manner, extending the HLR classification to a more detailed classification and to smaller catchments than are included in the national delineation. The ability of the classification schemes to describe significantly different population of catchments in terms of a set of important hydrologic and ecosystem measures will be evaluated through the HO network.

<i>Table 2-1. Hydrologic landscape region (HLR) descriptions</i>
(1) Subhumid plains with permeable soils and bedrock
(2) Humid plains with permeable soils and bedrock
(3) Subhumid plains with impermeable soils and permeable bedrock
(4) Humid plains with permeable soils and bedrock
(5) Arid plains with permeable soils and bedrock
(6) Subhumid plains with impermeable soils and bedrock
(7) Humid plains with permeable soils and impermeable bedrock
(8) Semiarid plains with impermeable soils and bedrock
(9) Humid plateaus with impermeable soils and permeable bedrock
(10) Arid plateaus with impermeable soils and permeable bedrock
(11) Humid plateaus with impermeable soils and bedrock
(12) Semiarid plateaus with permeable soils and impermeable bedrock
(13) Semiarid plateaus with impermeable soils and bedrock
(14) Arid playas with permeable soils and bedrock
(15) Semiarid mountains with impermeable soils and permeable bedrock
(16) Humid mountains with permeable soils and impermeable bedrock
(17) Semiarid mountains with impermeable soils and bedrock
(18) Semiarid mountains with permeable soils and impermeable bedrock
(19) Very humid mountains with permeable soils and impermeable bedrock
(20) Humid mountains with permeable soils and impermeable bedrock

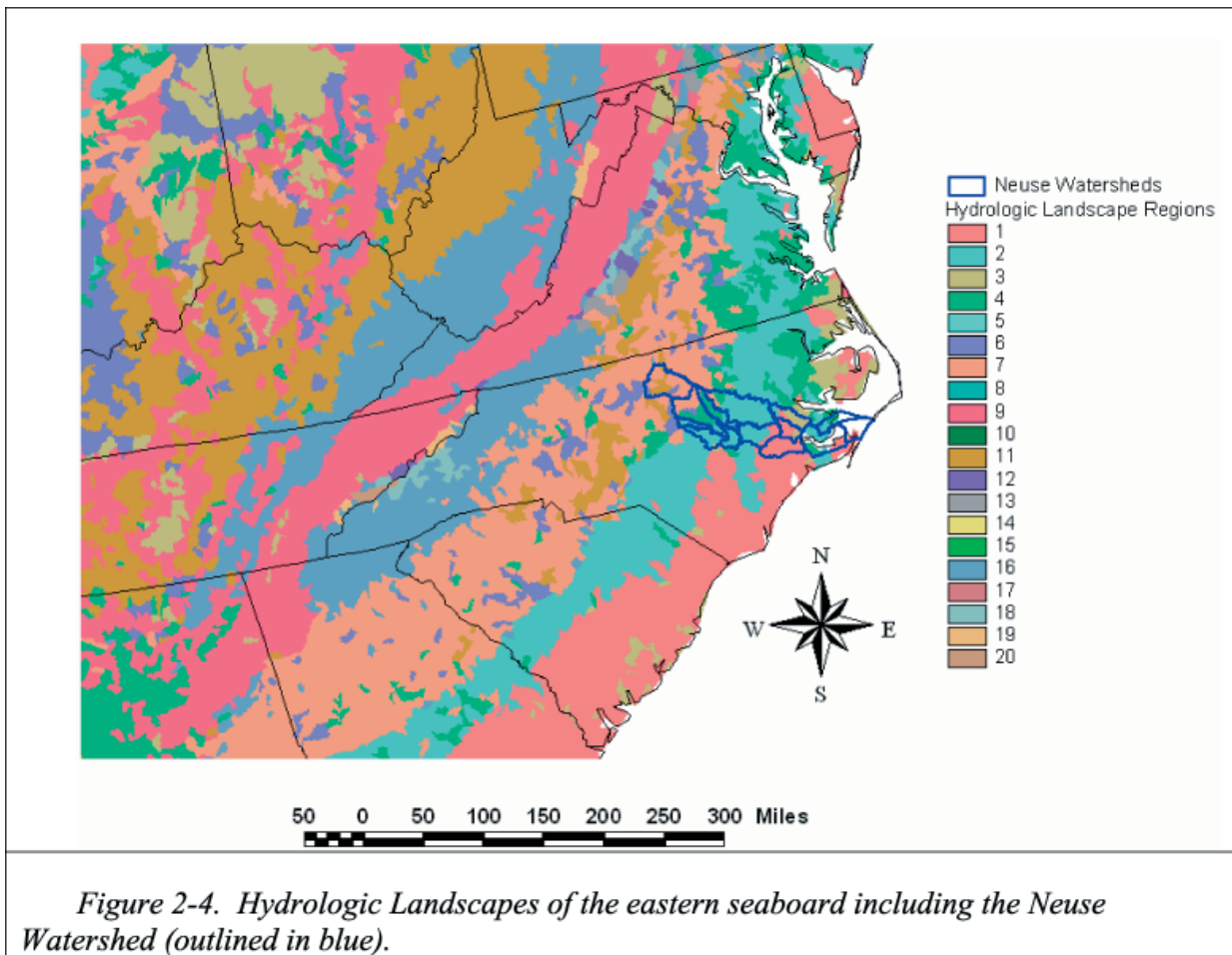


Figure 2-4. Hydrologic Landscapes of the eastern seaboard including the Neuse Watershed (outlined in blue).

2.5 Framework for organization of hydrologic measurements

While we have developed an integrated framework for the science goals and the requirements for the hydrologic measurements, the observatory must be constructed and each measurement must be planned in a careful detailed manner, while considering this framework and the inherent cost constraints and tradeoffs. In the following chapters, we present these more detailed designs, plans and instrumentation for the Neuse River basin. The organization of these chapters follows the schematic diagram presented in Figure 2-5.

We then present plans for intensive field campaigns, application of remote sensing, and development of hydrologic modeling that will take advantage of the capability of the observatory and present the plans for integrating social sciences within this observatory.

Core measurements and field campaigns carried out within the hydrologic observatory

will require a phased or adaptive implementation strategy. The strategy will initially focus on characterization of static variables (fig. 2-5) relating to the landform, physiography, geology, landuse, river network, soils, etc. Characterization of static variables is outlined in Chapter 3. In Chapters 4-9, the dynamic variables of surface water flows, precipitation, groundwater and soil moisture, etc, are discussed in separate chapters. Figure 2-5 illustrates the connections, feedbacks, and demonstrates the static or dynamic linkages among the chapters.

2.6 References

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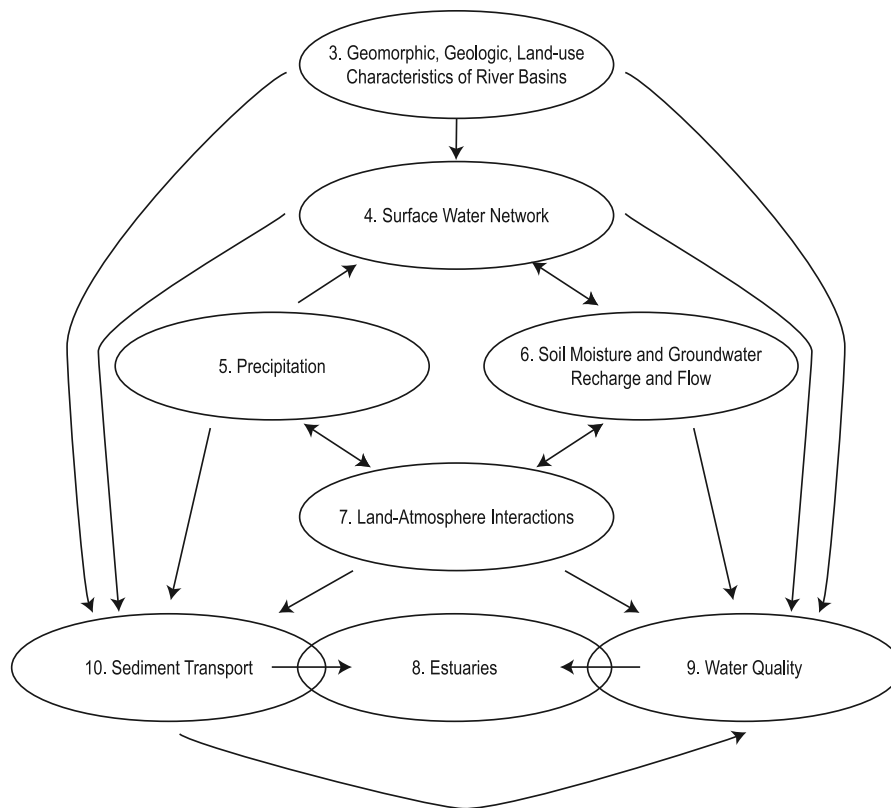


Figure 2-5. Dependencies among succeeding chapters in this report.

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3. Watershed Characteristics

Watershed characteristics such as topography, geology, soil properties, and land use are all critical for HO landscape characterization. These types of information may require measurement or compilation only once, or infrequently after significant changes.

3.1. Topography

Digital Elevation Models (DEMs) provide crucial information for hydrologic modeling. Although the utility of DEMs may be limited due to insufficient vertical resolution, DEM quality and resolution are rapidly improving. USGS accuracy standards for 7.5 minute data call for a vertical accuracy of 15 meters (USGS Data Users Guide 5) and much of the data (approximately 90%) is accurate to 7-8 m. This accuracy may be inadequate to model water flow, particularly in relatively flat areas with significant agricultural drainage such as the NC coastal plain area of the Neuse Watershed.

To better meet the needs of data users, the USGS has produced and is continually maintaining the National Elevation Dataset or NED. The process of creating this seamless data set removes data artifacts and performs edge matching, improving the quality of the original quad sheet data. The data are continually updated with "best available data." As such, the 10m source DEMs are being actively integrated in the NED data. A 3m product is also being incorporated into the NED. A detailed overview on the NED is presented by Gesch et. al. (2002). Other sources of DEMs are also being examined for integration in the NED, including LIDAR and IFSAR data (Gesch et al. 2002).

In North Carolina, the NC LIDAR (Light Detection and Ranging) program has provided a generational improvement in available DEMs for the Neuse Watershed. This program addresses concerns of inadequate vertical resolution, particularly with respect to flood plain mapping in the hurricane and flood prone coastal plane. The data have an accuracy of 20 cm in the coastal plain and 25 cm in the inland counties. The data sensor was flown in 2001 between January and March (leaf off) and the Neuse River watershed has been completed, with elevation data on

line at www.ncfloodmaps.com. There are three main products. One is the Bare Earth Terrain (BE), which is the actual mass points and break lines used to create the DEMs. Density of spot elevations is very high in open fields, and falls off significantly under forest canopies (e.g., Figure 3.1). However, even the lower spot height density in forested areas supports interpolation of a DEM at higher resolutions than other available sources. Two DEM products result: a 20 ft DEM and a 50 ft "hydro enforced" DEM, which forces the DEM to match stream and lake positions. Considerable user skill is often required to comprehend and manipulate LIDAR data, but the DEM20 and DEM50 products should be relatively easy to work with. Channel and floodplain cross sections have been produced for major rivers and streams to improve delineation of flood risk as part of a joint project with FEMA. Hydraulic modeling of flood inundation has also been carried out as part of the FEMA delineation.

Additional DEM sources are available, such as the Shuttle Radar Topography Mission (SRTM) data product at 30 m (1 Arc Second) and 90 m (3 Arc Second). The SRTM mission mapped nearly the entire land surface between 60 degrees north and 60 degrees south latitude. The 30 m data will be available only for the United States. The 30 m SRTM product is also available as seamless data, with the same restrictions as the 30 m NED data – free for a 30-degree square area in 100 MB sized files. The elevation accuracy of these data, however, is not readily available.

Other topographic related products are being developed. Hydrologic products developed from the NED are being generated by an effort parallel to NED, the USGS Elevation Derivatives for National Applications (EDNA) project (Verdin 2000; Kost and Kelly 2001). Similar testing and development with the NC LIDAR 20 and 50 ft DEM products by the USGS for the Neuse is underway (Verdin, personal communication).

3.2. Land Use, Land Cover (LULC), LULC change (LULCC)

There are a variety of Land Use Land Cover (LULC) data sets that cover the state of North

Carolina. The National Land Cover Data set (NLCD) has produced a LULC for the entire United States at a spatial resolution of 30 m. This is based on TM imagery centered around 1992, including scenes from 1990-1993. The NLCD LULC and related documentation are freely available on-line: <http://www.epa.gov/mrlc/nlcd.html>. The process has already been started for a follow-up LULC based on imagery centered on the year 2000.

The State of North Carolina has also produced a LULC. This LULC is at a spatial resolution of 28.5 m and is based on TM imagery collected from 1993–1995. This data set is distributed through the North Carolina Center for Geographic Information (<http://cgia.cgia.state.nc.us/cgia/>) on a cost recovery basis. Documentation and accuracy assessment is available at: <http://cgia.cgia.state.nc.us/cgdb/refdocs/lc96/index.html>. There are no formal plans for this LULC to be updated. Other LULC for the state do exist, such as The Nature Conservancy's NC GAP data, however these data have no accuracy assessment or metadata at this time.

Other LULC data sets are available for portions of North Carolina. The US EPA Landscape Characterization Branch in Research Triangle Park, NC, has produced an excellent LULC map for the Neuse Watershed (Lunetta et al. 2000). This LULC is based on both TM and Spot imagery from 1997 and 1998. This data set includes extensive accuracy information. The EPA Neuse

LULC has a spatial resolution of 15 m with a 0.1 hectare minimum mapping unit (MMU) in riparian zone (within 30 meters of streams, river shorelines, etc.) and a 0.4 hectare MMU outside the riparian zone, making this useful to address finer scale issues in this watershed. These data are freely available to the public. There are no current plans for this LULC to be repeated in the Neuse or duplicated in additional watersheds. A moderate resolution (250m cell) LULC is being prepared for the Albemarle-Pamlico watershed by the same group.

3.3. Soils

Application of models for estimation of fluxes and residence times may be constrained by insufficient knowledge of soil hydraulic properties. Soils data from online databases including STATSGO and SSURGO databases (USDA 2004) are available for the Neuse Watershed (Figure 3.2) and can be used with pedotransfer functions to estimate hydraulic parameters. Pedotransfer functions such as implemented by the Rosetta pedotransfer software (Schaap et al. 2001), transform available soil data into hydraulic parameters including water retention and hydraulic conductivity that are difficult or expensive to measure directly. A hierarchical approach is used to estimate hydraulic parameters based on varying levels of soil data from State Soil Geographic (STATSGO) database that is at a 1:250,000 scale and Soil Survey Geographic (SSURGO) database at a scale of 1:24,000:

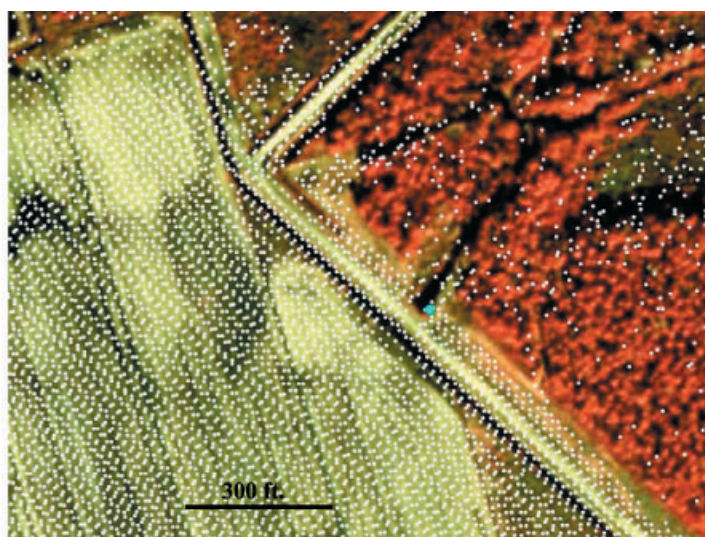


Figure 3.1. BE LIDAR points in forest and agricultural areas in eastern NC.

1. Soil texture classification
2. Sand, silt, and clay percentages
3. Values in (b) plus bulk density
4. Values in (c) plus water retention at -3 m head
5. Values in (d) plus water retention at -150 m head

Increased knowledge of soils data (i.e., (5) vs. (1) above) results in greater accuracy in the estimated retention function parameters and saturated hydraulic conductivity values. The STATSGO database includes the following attributes: clay content, organic material, soil water capacity, permeability, infiltration, drainage, and slope. There are two versions of the SSURGO database. The SSURGO version 2 database provides more detailed soil texture data than either the SSURGO version 1 or the STATSGO database. In addition to the basic soil data, the SSURGO version 2 database provides soil water retention data at -3.3 and -150 m matric potential head, which neither the SSURGO version 1 nor the STATSGO database provide.

In addition to online data, hydraulic properties of subsurface materials will be

determined at locations where detailed subsurface measurements (described in later chapters) will be made. These determinations will include field and/or laboratory measurement of saturated hydraulic conductivity and laboratory measurement of water retention for the different soil textures encountered at the site. Collocated in-situ measurements of water content and matric potential will be used to establish in-situ water retention functions.

3.4. Nested watershed sampling design

In order to generate core data useful for estimating stores, fluxes, residence time and flowpaths at multiple scales, the full Neuse Watershed needs to be partitioned into a nested set of subwatersheds that will span distinct assemblages of hydrologic landscapes and several orders of magnitude in drainage area. We propose to gauge catchments ranging from 10^{-1} km², which is approximately the area at which surface flow becomes channelized in the Neuse Watershed, through the full watershed at 10^4 km². This includes five orders of magnitude in drainage area, sufficient to characterize scaling behavior in the core properties of the watershed. More detailed measurement and characterization of smaller, focal catchments will be embedded within progressively larger watersheds, allowing critical evaluation and development of hydrologic

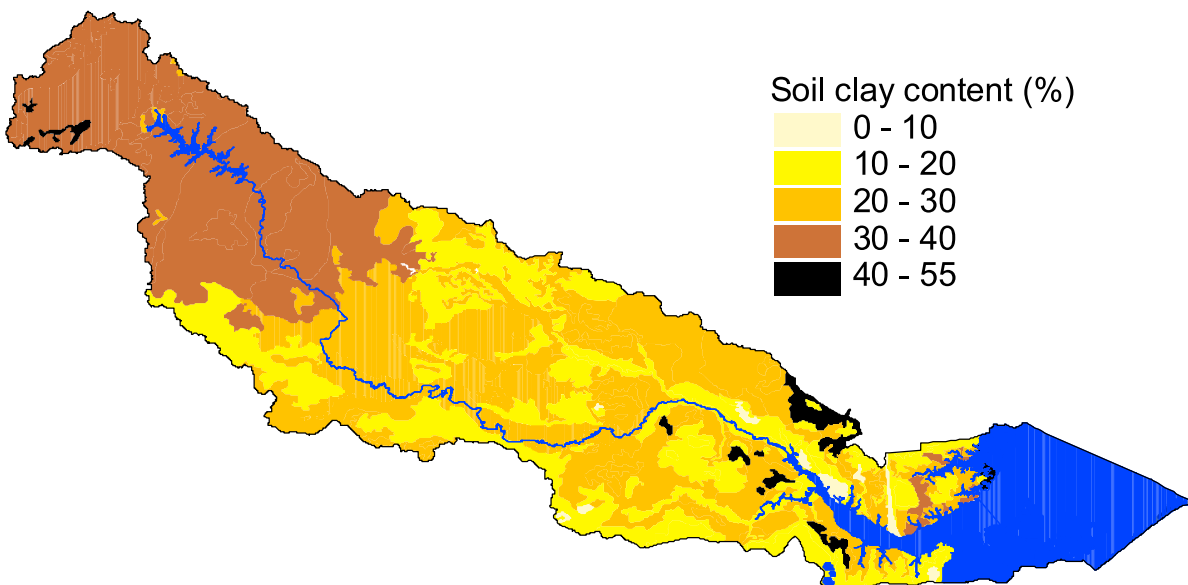


Figure 3.2. Distribution of clay content in the Neuse Watershed based on STATSGO data.

scaling strategies. The sampling design needs to address upland sources of runoff, solutes and sediment, land-atmosphere exchange, stream water flow and quantity, as well as interface behavior within the nested subwatershed structure.

Therefore, the sampling scheme adopted by the Neuse Watershed HO is centered around measurements co-located at or near the set of stream gauges, a set of terrestrial sampling sites within the drainage areas of the gauges, and a comprehensive nested design for precipitation measurement. The backbone of our sampling design includes these three domains of measurement and characterization:

1. the stream network structure of discharge, solute flux and transformations, and sediment mobilization and routing,
2. land surface sources and sinks of water, energy, nutrients and sediment, measured at a set of land-atmosphere instrumented sites along flowpaths representative of the drainage areas contributing to the stream gauges, and
3. multi-resolution precipitation measurements with high resolution precipitation available for smaller, focal catchments.

Significant design questions in the design of this hierarchical measurement system then include:

1. How many catchments at each drainage area order of magnitude need to be gauged?
2. What range of characteristics, including hydrologic landscape category, land cover and human activity, should be sampled?
3. What range of core measurements and datasets need to be generated, and at what spatial and temporal frequency? This includes measurements of in-stream, terrestrial, and atmospheric stores, fluxes, residence times, and flowpaths of water and its major constituents.
4. How should this design be adapted over time to new information?

The terrestrial instrumentation sites will measure the space-time distribution of those processes and stores determining land-atmosphere exchange of water, energy and biogeochemical constituents, extending into surface/groundwater exchange, storage, and flux. In the following chapters we begin by outlining the set of stream discharge gauges that will be installed, the rationale for new gauges over and above what currently exists in the Neuse, and the set of surface, subsurface, and meteorological measurements that will be co-located to characterize storage, flux, residence time, and flowpaths within the set of nested catchments.

For the most part, these chapters follow a standard template that first outlines key science questions and/or hypotheses that instrumentation and sampling are designed to address for each of the major hydrologic cycle components. This presentation of questions/hypotheses is followed by description of the instrumentation and sampling density within the nested catchment design established in the surface water (stream discharge) sampling scheme. In all cases, terrestrial (surface and subsurface) instrumentation are implemented along representative flowpaths or hydrologic landscape positions within the drainage areas delimited by the stream gauge network.

It is important to note that the instrumentation design is not constructed as a random sampling in order to estimate HO-wide statistical parameters of hydrologic cycle components. Instead, it is a stratified and targeted sampling design to be used in association with a set of existing and developing hydrologic models to generate estimates of the basic hydrologic properties at multiple scales, and to address specific hypotheses concerning the Neuse HO. Positions given in the design are approximate and will depend on site permissions and the suitability of a reach as a gauge site.

As mentioned above, stream gauging will sample discharge and water quality parameters over five orders of magnitude in terms of drainage area. The lower end of this range of scales would be the small headwater catchment, at the up-stream limit of perennial streams (~10 ha). Progressing downstream, generations of additional sites at different scales along the

Neuse River will produce core data to investigate how streamflow discharge and its constituents “accumulate” along the course of our major river. Measurement along the mainstream will be complemented by discharge sampling in tributaries to the Neuse River (and, in a few cases, tributaries directly to the estuary, as the estuary is the water body that defines the overall boundary of the HO).

Dropping down one “step” in spatial scale from the full Neuse River, most of the area of the HO is contained in 17 intermediate-size watersheds (11 drain to the Neuse River, 2 drain directly to the Neuse estuary, and the remaining 4 drain to another of the 11 that drain to the Neuse River). This intermediate scale can be covered completely (no subsampling is necessary), as 17 is a relatively modest number of gauging sites. Below this scale (for smaller watersheds), it is not feasible to “exhaustively” gauge the HO (to cover every site in the HO, for several smaller scales); therefore, at smaller scales, subsampling is necessary.

The design recognizes 4 broad zones of the watershed (from inland to the coast) defined by different combinations of topography, geology, and land use. These zones helped guide the choice of stream gauging sites for smaller watersheds. There are intermediate-size watersheds in each of the 4 zones. The design calls for picking 6 intermediate-size watersheds for in-depth study at smaller scales: 1 from each of the 4 zones, plus an additional watershed in each of 2 zones having significant urban areas (so that intermediate-size watersheds with and without significant urban influence will be studied in these 2 zones).

In each of the 6 intermediate-size watersheds chosen for in-depth study, stream discharge will be measured at 6-8 sites across a range of scales, from headwater catchments with one dominant land use to the mouth of the watershed. This design allows analysis of scale effects within each and comparison of these effects among the 6 (i.e., across 4 different “hydrologic zones” or

landscapes, including comparison of watersheds with and without significant urban area in 2 of the 4 zones).

Finally, given that the Neuse estuary defines the boundaries of the HO and quantifying inputs to the estuary from its watershed is a central goal, discharge measurements will be made on 5 of the larger tidal tributaries that drain directly to the estuary from its north and south shores.

3.5 References

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4. River/Stream Discharge and Overland Flow

4.1. River/Stream Discharge

4.1.1. Key Science Questions

- a. What are the surface water inputs to the Neuse estuary from its watershed, and how do they compare with the groundwater, rainfall, and evaporative fluxes to/from the estuary?
Needed: Discharge measurements on rivers and streams flowing into the estuary, and estimates of the other water fluxes mentioned above for comparison.
- b. How does river discharge per unit contributing area (Q/A) vary with spatial scale along the Neuse River, from headwaters to coast? What are the main controls on this variation (rainfall, soils, topography, point sources, land use and land cover) and do they change with location/scale?
Needed: River/stream discharge measurements at different scales (small watershed to full Neuse River), together with data on the possible controls listed above, and a spatial analysis relating the controls to the discharge.
- c. Are there major differences in Q/A from intermediate-size watersheds in the four different hydrologic zones (landscapes) of the Neuse Watershed (Upper and Lower Piedmont, Upper and Lower Coastal Plain)? Are there different relations between Q/A and watershed scale in the different zones, and if so why?
Needed: River/stream discharge data on the 17 intermediate-size watersheds (150-2600 km² in area) that make up >70% of the Neuse estuary watershed, at the outlets of the watersheds and also at different spatial scales within them; also, data on the possible controls listed in the previous question, and a spatial analysis relating the controls to the discharge.
- d. How can information on water discharge from small watersheds with one dominant land use be used to estimate discharge from much larger watersheds of mixed land use?
Needed: Data on stream discharge from the small watersheds, understanding of controls on discharge, and a modeling framework/analysis for scaling up.
- e. Do existing watershed models adequately predict hydrologic fluxes (especially river discharge) and stores? If not, why not, and what improvements are needed?
Needed: Data on river/stream discharge, precipitation, ET, and other hydrologic fluxes and stores, and modeling exercises that make use of the data in calibration and post-calibration prediction and sensitivity analyses.
- f. Is the water budget of the Neuse watershed and/or its sub-watersheds changing, and if so, where (the Piedmont? Coastal Plain? sub-areas of these zones? everywhere?) and by how much? What are the implications for future flooding and low flow under likely climate change scenarios?
Needed: Long-term data on river/stream discharge, precipitation, ET, and other hydrologic fluxes and stores, with high temporal resolution at different scales across the Neuse watershed, and model-based water budget calculations; also, predictions of flood frequency and extent under future climate and land use scenarios.
- g. What are the rates of groundwater input to (or loss from) rivers/streams, and how do they vary with scale and other factors (geology, land use)?
Needed: Rates of shallow groundwater exchange with rivers/streams at different scales (small stream to Neuse River) together with spatial analysis of relationships between groundwater discharge and possible controls (geology, land use, etc.).
- h. Are there strong seasonal variations (linked to temperature, hydrologic status,

natural plant cycles, or agricultural operations) in the answers to the questions above, and are these variations well represented in and predicted by existing models?

Needed: For the measurements and modeling analyses discussed above, temporal coverage that spans all seasons and samples the variability within seasons (which for some fluxes may be large on time scales of several hours), together with data on the seasonal variations in temperature and the other potential influences listed in the question.

- i. What is the improvement in predictive performance (outside the calibration period) of watershed hydrologic/nutrient models when new data on river/stream discharge at different scales across the Neuse watershed are used in calibration?
Needed: Predictions (outside the calibration period(s)) of river/stream discharge using appropriate models calibrated both with and without the new data.

4.1.2. Observing Strategy

Fifty-four new river/stream gauging sites are proposed to collect data that will be used to address the research questions above and others. The 54 new sites will complement existing USGS gauging sites (some of which date back to the 1920s). All sites would have continuous discharge data collection and at least flow-weighted composite sampling for water quality, with a program of additional high-frequency discrete-sample event sampling that will also reach many of the sites. Collection of water quality and sedimentary data at these sites is discussed in Chapters 9 and 10, respectively.

Neuse River: 5 new sites. The discharge gauging design for the Neuse River itself includes 4 new sites and 4 existing USGS gauging sites (the latter, from upstream to downstream, are the Falls Lake Dam, Goldsboro, Kinston, and Fort Barnwell). The additional spatial coverage from the 4 new sites will give an improved quantitative spatial picture of how discharge varies along the length of the Neuse River. The new sites, from upstream to downstream, are (1) just upstream

of the Crabtree Creek confluence, (2) just downstream of the Black Creek confluence, (3) just upstream of the Mill Creek confluence, (4) just upstream of the Bear Creek confluence, and (5) at the mouth of the Neuse River, near New Bern.

Lands Immediately Adjacent to Neuse Estuary: 5 new sites. A number of small tidal streams drain directly into the Neuse estuary from very low-relief marshy and agricultural areas immediately adjacent to the estuary. The proposed river/stream gauging design for the Neuse HO calls for gauging the mouths of the 5 largest among these tidal streams (2 on north shore of the estuary and 3 on south shore). Discharge from the remaining smaller ungauged streams along the estuary will be estimated based on discharge results from the 5 gauged streams.

Intermediate-Size Watersheds: 17 new sites. Over 70% of the Neuse estuary watershed is made up of 17 intermediate-size watersheds (150-2600 ha in area) listed in Table 4-1. Knowing river/stream discharge at different spatial scales is relevant to a number of research questions, and gauging all 17 of these intermediate-size watersheds is a feasible task that seems the logical first-step downward in scale from gauging the full watershed inputs to the estuary. Land not in these 17 watersheds is either in small areas adjacent to the Neuse River or in the low-relief areas immediately adjacent to the estuary. Of the 17, 11 directly to the Neuse River or Falls Lake (the only reservoir on the Neuse River), 2 drain directly to Neuse estuary, and 4 are tributaries to 2 of the 11 that drain directly to the Neuse River (3 drain to Contentnia Creek and 1 to the Little River). Though 10 of the 17 currently have a USGS gauging site somewhat near the watershed outlet, the HO will investigate the feasibility of establishing new gauging sites closer to the watershed outlets (e.g., closer to the confluence with the Neuse River or to the mouth at the Neuse estuary), so these are currently counted as new sites. If use of these “ideal” sites is financially or logistically infeasible the HO would rely on continuation of the nearby USGS gauges.

Intensively-Gauged Intermediate-Size Watersheds: 27 new sites. Discharge measurements at a range of watershed scales (down to roughly 10 ha) are needed to address many of the important research questions related

to spatial scale. Given that it is clearly not practical to gauge all watersheds within the Neuse HO down to this scale, choices must be made regarding which will be gauged. The approach taken was to choose a subset of the 17 intermediate-size watersheds mentioned above for discharge measurement across a range of scales. These intermediate-size watersheds were chosen from the 17 to span the full range of physiographic and land use features in the Neuse estuary watershed. The first step was identifying where each intermediate-size watershed falls with respect to 4 zones distinguished on basis of geology, topography, and land use within the Neuse estuary watershed. The zones are based on inspection of topographic, geologic, and land use maps; from east to west they are:

- Zone 1, lower Coastal Plain: very flat, some ditching, significant agriculture but less than in Zone 2, more forest and wetland than in Zone 2, no large urban areas in the intermediate-size watersheds (New Bern is right on the estuary), clastic sedimentary geology similar to most of Zone 2
- Zone 2, upper Coastal Plain: more agriculture and less wetland and forest than Zone 1, some ditching, little urban area in most intermediate-size watersheds (the largest, Kinston and Goldsboro, are right on the Neuse River), small city of Wilson is in the Contentnia Creek watershed, mainly clastic sedimentary geology (upper part reaches metamorphic rocks)
- Zone 3, lower Piedmont: more forest, lower agriculture and wetland than Zones 1 or 2, some watersheds with great urban influence (in the Raleigh area) and others with very little urban influence, higher relief than Zones 1 and 2, granitic and metamorphic rocks with clayey saprolite
- Zone 4, upper Piedmont: mainly forest, minor agriculture, all drainage is to Falls Lake (the only reservoir on the Neuse River), some urban influence near Durham, higher relief than Zones 1 and 2, granitic and metamorphic rocks with clayey saprolite.

River/stream discharge measurements across a range of spatial scales are proposed

for 6 intermediate-size watersheds: One from each zone plus one additional watershed in each of Zones 2 and 3 because of significant urban areas in these zones (allowing for selection of watersheds with and without significant urban effects in Zones 2 and 3). Discharge measurement sites within these 6 intermediate-size watersheds will cover a range of spatial scales, down to, at the small end of the spectrum, several small watersheds that each have a single dominant land use (forest, agriculture, or urban). The 6 intensively gauged intermediate-size watersheds proposed are listed below; in each case the discharge gauging site at the watershed outlet is not included in the description below of new sites needed (because it is counted above under "Intermediate-Size Watersheds"):

- Zone 1 – Trent River: no significant urban area (except right at the mouth of the river, on the estuary), 2 existing USGS discharge gauging sites. Three more sites are needed for a total of 5 in the design, the new sites being 1 to define a mainly-agricultural small watershed, 1 to define a mainly-forested small watershed, and 1 other on the main channel of the river.
- Zone 2 – Little Contentnea Creek: no significant urban area, current discharge gauging at USGS sites S6 (below the confluence with Middle Swamp), S5 (Middle Swamp), and S2/S3 (Lizzie small agricultural watershed research site). Three more sites are needed for total of 6 in the design, the new sites being 2 more on the main channel and 1 to define a mainly-forested small watershed.
- Zone 2 – Toisnot Swamp: similar to Little Contentnea but with significant urban influence near Wilson. This watershed has no existing discharge gauging sites, 6 new sites are needed: 3 on the main channel (2 upstream of Wilson, 1 downstream of Wilson) and 3 others to define small watersheds (mainly-agricultural, mainly-forested, and mainly-urban).
- Zone 3 – Swift Creek: significant urban influence (between Raleigh and Cary) plus 2 reservoirs (Lake Benson and Lake

Name	Area, km ²	Zone	Urban %	Farm %	Forest %	Wetland %	Water %	Other %
Flat River	454	4	12.46	26.32	59.53	0.85	0.73	0.14
Little River (West)	272	4	12.79	24.38	60.17	1.55	0.94	0.18
Eno River	402	4	22.94	16.74	58.19	1.13	0.7	0.33
Little River (East)	816	3	18.25	33.52	36.93	9.77	0.98	0.56
Black Creek	274	3	23.88	32.33	34.79	6.81	1.6	0.61
Buffalo Creek	151	3	18.61	29.58	39.37	10.91	1.04	0.48
Middle Creek	341	3	27.01	23.52	41.01	7.03	0.98	0.47
Crabtree Creek	376	3	59.14	1.17	36.32	1.67	1.04	0.71
Swift Creek (West)	400	3	32.91	17.23	42.95	4.9	1.73	0.28
Mill Creek	451	3						
Bear Creek	173	2	11.05	60.38	22.17	5.52	0.73	0.15
Nahunta Swamp	253	2	9.24	51.08	30.82	8.15	0.34	0.36
L. Contentnea Creek	470	2	5.99	50.43	31.23	11.88	0.42	0.15
Contentnea Creek	2608	2	12.48	43.49	31.48	11.47	0.83	0.29
Toisnot Swamp	327	2	17.65	40.86	27.53	12.88	0.78	0.37
Swift Creek (East)	859	1	6.09	31.16	35.7	25.57	0.4	1.14
Trent River	1153	1	4.04	28.97	42.91	23.43	0.38	0.3
TOTAL	9780							

Table 4.1. 17 intermediate-size watersheds in the Neuse watershed HO. Zones are explained below. "Other" includes minor categories (grassland, barren land, unclassified land). Bold font indicates 6 watersheds proposed for intensive gauging.

Wheeler) and 1 existing USGS discharge gauging site. Six new sites are needed for a total of 7 in the design, the new sites being upstream and downstream of each reservoir (1 of these already exists and is considered part of the design), 1 in the lower part of watershed, 1 to define small watershed in the urban/suburban headwaters, 1 to define a mainly-forested small watershed.

- Zone 3 – Buffalo Creek: no existing discharge gauging, no significant urban

influence. The design for this watershed is similar to that for Toisnot Swamp except for the lack of a small urban watershed. Five new discharge gauging sites are needed.

- Zone 4 – Eno River: 2 existing USGS discharge gauging sites and 1 Duke Forest site are considered part of the design. Four new discharge gauging sites are needed for a total of 7, 1 on the main channel of the West Fork Eno River just upstream

of its confluence with the East Fork, 1 to define a small mainly-forested watershed downstream of the Duke Forest site, 1 to define a small mainly-urban watershed near Durham, and 1 to define a small mainly-agricultural watershed in the headwaters of the West Fork Eno River.

This design leads to 14 small watersheds with single dominant land use shown in Table 4.2

Dominant land use	Neuse watershed Zone				TOTAL
	Zone 1	Zone 2	Zone 3	Zone 4	
forest	1	2	2	1	6
agriculture	1	2	1	1	5
urban	0	1	1	1	3
TOTAL	2	5	4	3	14

Table 4.2. Neuse Subwatersheds

Methods. Methods will include standard stage-discharge relations and continuous stage measurements at sites amenable to this approach and AVM or ADCP technology at other sites (e.g., sites with “backwater” conditions or other features that prevent discharge from being a single-valued function of stage). Calibration efforts (e.g., points on rating curves) will be based on discharge data from a mobile ADCP system (e.g., Sontek River Surveyor).

Implementation Schedule. River/stream discharge measurement sites will be set up and data collection initiated over the first 3 years of HO operation. The proposed schedule is:

- Year 1: 5 sites on the Neuse River, 6 on outlets of intensively studied intermediate-size watersheds, 2 on outlets of small tidal creeks along estuary, total of 13 this year
- Year 2: remaining 11 on outlets of intermediate-size watersheds, remaining 3 on small tidal creeks along estuary, and sites upstream of watershed outlets in Eno River (4) and Buffalo Creek (5), total of 23 this year
- Year 3: sites upstream of watershed outlets in Swift Creek (6), Toisnot Swamp (6), Little Contentnia Creek (3), and Trent River (3), total of 18 this year.

4.2. Overland Flow

4.2.1. Key Science Questions

What is the frequency and occurrence of overland flow in different physiographic regions (hydrologic landscapes) within the Neuse River watershed?

- Hypothesis:** During extreme rainfall, significant portions of the landscape may experience overland flow due to saturation from both above and below depending on soil type, layering, and groundwater depth. Saprolitic soils in Piedmont areas may saturate from above during intense convective rainfall.
Needed: One hillslope, plot, or field-scale study site in each of the three major physiographic regions in the Neuse Watershed (Piedmont, inner, and outer coastal planes). These sites shall be instrumented to detect overland flow using interception troughs and high-volume tipping bucket flow gages. Downslope regions may use weirs or flumes. These hillslope sites shall be co-located with nested soil moisture monitoring network sites, and shallow groundwater observation wells to aid in identifying runoff production mechanism.

- Hypothesis:** Regions of the coastal plane that are dominated by sandy soils will experience overland flow very infrequently, except during extreme events. However, saprolite soils in the Piedmont may produce runoff under extremely wet or dry antecedent moisture conditions and high intensity rainfall. We hypothesize that

existing watershed models using available soils data will be able to represent these differences reasonably well at the hillslope scale but perhaps not at much larger scales.

Needed: Overland flow detectors as in 1a) co-located with nested soil moisture monitoring network sites, and comparison of model-predicted and measured overland flow.

- c. **Hypothesis:** Transport of nitrogen from fields irrigated with animal waste infrequently occurs as overland flow. However, when it does, contributions to stream loadings of nutrients and pathogens can be significant. Animal waste ponds are designed to contain extreme events, but extended wet periods can cause them to fill with water. This filling necessitates partial draining by accelerated spray irrigation, even when not needed to prevent overtopping of animal waste ponds. In certain soil/groundwater conditions, this might lead to overland flow runoff of animal waste to rivers and streams.

Needed: Use of existing NC-DWQ and USGS intensive study site, enhanced with monitoring instrumentation on animal waste pond levels, irrigation pumps, and overland flow detectors at likely outflow points from fields to receiving waters. These detectors will be connected to automated samplers (e.g. ISCO).

Given high rates of urbanization in portions of the Neuse River watershed, how will the future Neuse River respond to extreme events?

- a. **Hypothesis:** Extensive urbanization in the Neuse River watershed is changing the frequency distribution of storm runoff, particularly in the rapidly expanding Raleigh-Durham region. Recent studies have provided an indication that increased drainage efficiency associated with urbanization is more significant than changes in impervious coverage. However, increases in drainage efficiency are partially offset by engineered stormwater retention/detention facilities. **Needed:** Paired basin studies in a developed and an adjacent undeveloped or developing catchment with similar

soils, relief and catchment area. Acquisition of storm drainage network geometry data. Increase in stream gauging in small drainage basins, and in some engineered pathways (e.g., sewers) interlinked with the natural system in developing watersheds.

- b. **Hypothesis:** The net effect of urbanization and stormwater management planning is to decrease the quantity of runoff associated with frequent rainfall events and increase the quantity of runoff due to less frequent and extreme events. **Needed:** Same as 2.a. and precipitation network.
- c. **Hypothesis:** Soil moisture is a key parameter affecting surface runoff in urbanized catchments. Increases in impervious fraction do not negate the impact of soil moisture on surface runoff generation in urbanized areas. **Needed:** Same as 2.a.

4.2.2. Observing Strategy

The science questions in this overland flow section can be divided into “observatory-wide” compare/contrast and “urbanization” questions. In each case, observations are limited to hillslope, plot, field, or catchment/subdivision scale depending upon the setting. Co-location of all small-scale study sites will be coordinated with proposed meteorological and soil moisture observing sites.

The observation sites established in this chapter will provide facilities for small-scale PI research in a way that is unique to the observatory instrumentation. Agricultural sites will enable hillslope to field-scale observations of hydrologic fluxes of water and solutes. Co-located soil moisture and hydrometeorological instrumentation will help close the water balance and provide data required by a wide range of potential PI studies.

Observatory wide compare/contrast observations: Three sites will be selected, one each in the Piedmont, inner, and outer coastal plain. It is expected that each of these three sites will include forest and agricultural land-uses.

The sites will cover an area of 50-100 ha with the emphasis on hillslope, plot, and field-scale observations.

Paired-basin Developed/Developing observations: Two basins will be selected in the Raleigh-Durham area. These basins will be

similar in every respect (size, aspect, soils) but will differ in degrees of urbanization. One shall be developed, the second shall be either undeveloped or in the early stages of development. Continuous data collection over a number of years will allow testing of hypotheses previously stated.

5. Precipitation

Rainfall is the major forcing for many hydrologic processes. The Neuse Watershed (NW) HO will be equipped with sensors capable of providing comprehensive information on its space-time distribution. Rainfall is observed by rain gauge networks, weather radars, and meteorological satellites. At the current time the capabilities of satellites to provide quantitative estimates of rainfall are limited and we do not consider them for the Neuse Watershed. The precipitation observation system will provide estimates of precipitation for the full watershed, with progressively finer measurement density and resolution for the nested, focus watersheds described above. Characterization of precipitation regime will address the three dominant sources of precipitation in the Neuse Watershed: mid-latitude cyclonic events, tropical systems, and convectional events.

5.1. Key Science Questions

How does precipitation vary in space and time across the range of scales represented within the Neuse Watershed?

- a. **Hypothesis:** Precipitation variability in space and time depends on rainfall regime and intensity, physiography, and vegetation.
Needed: Dense networks of rain gauges and disdrometers that cover distances as short as 0.5 km and as long as the operational networks currently in place (about 50 km). The disdrometers allows studies of variability of several characteristics of precipitation that can be calculated as different moments of the drop size distribution. These include, for example, optical extinction, kinetic energy, and radar reflectivity.
- b. **Hypothesis:** Precipitation exhibits multiscaling properties conditional on the factors generating vertical air motion, leading to the major categories of storms experienced in the Neuse Watershed: mid-latitude cyclonic events, tropical systems, and convectional events.
Needed: Scanning weather and vertically pointing radars. As rainfall variability is affected by physical processes that change

in horizontal and vertical direction as well as in time, weather radars provide a wide range of spatial and temporal scales at high resolution. Similar observational range is not possible with in-situ observing systems.

- c. **Hypothesis:** Runoff production, soil erosion, and urban basin response depend on small-scale variations in precipitation, soil moisture, vegetation, and land use/land cover.

Needed: Specialized networks of small and inexpensive radars. A network of four X-band Doppler polarimetric radars can provide high-resolution (100×100 m²) coverage of an area of about 500 km². If the radars are operated as a synchronized network the effects of signal attenuation, observational noise, ground clutter, as well as many other factor that plaque radar-rainfall estimation can be effectively mitigated.

We could have listed many more questions/hypotheses, but since rainfall affects many other processes, it is going to be one of the core variables that will be observed in any Hydrologic Observatory. Thus, what we discuss below is a rather generic strategy that can provide both high-quality core data as well as hypothesis specific information. Before we present our design of rainfall observing system for the Neuse Watershed we review the currently available sensors and data.

5.2. Observing Strategy

5.2.1 Current Rainfall Observations.

There are several Weather Surveillance Radar Doppler systems (WSR-88D) monitoring precipitation systems over the state of North Carolina and the Neuse Watershed. There are also other operational systems such as Federal Aviation Administration's Automated Surface Observing System (ASOS) located at the airports, AWOS which include rain gauges. The office of State Climatologist operates the EcoNet, a network of automated weather stations distributed over the state. In and around the

basin there are about 15 such stations. Outside of the Neuse, near Charlotte, NC, the United States Geological Survey operates a real-time dense network of some 78 tipping bucket gauges. Due to the short inter gauge distance, the data provide information on the statistical characteristics of rainfall in the region.

From the six WSR-88D radars that can “see” over the basin only two provide useful information: KRAX in Raleigh and KMHX in Morehead City. Other radars are simply too far and cover only small portions of the basin. The KRAX and KMHX are located near the opposite ends of the basin and their overlap covers a significant part of the basin. This is a very good situation as the two systems provide some level of redundancy and potential for error reduction. Both radars are operated by the National Weather Service (NWS) and provide standard precipitation products (Fulton et al. 1998; Crum et al. 1998; Serafin and Wilson 2000.) The most popular product is hourly accumulation at the spatial resolution of about 4 km by 4 km. This product is enhanced by the NWS River Forecast Center in Atlanta which covers the Neuse Watershed.

The resolution of this product is adequate for many operational purposes of streamflow and flood forecasting but is too coarse for research and simulation of hydrologic response of small basins (Ogden and Julian 1994; Sharif et al. 2002; Sharif et al. 2004.) Also the quality of the operational NWS precipitation products is not well investigated. Previous studies (Smith et al. 1996; Young et al. 2000; Vieux et al. 2000) demonstrated various shortcomings but statistical characterization of radar-rainfall uncertainty remains an unsolved problem (Krajewski and Smith 2002; Ciach and Krajewski 1997; Habib and Krajewski 2002; Ciach et al. 2002).

5.2.2 Proposed Rainfall Observing System

We propose a two-prong approach to a rainfall observing network in the Neuse Watershed. First, we propose to use products developed based on Level II data from two WSR-88D radars enhanced by additional ground based sensors. Second, we propose to use a specialized network of small inexpensive radars that can provide rainfall estimates at higher resolution than the WSR-88D for focus catchments. The first

network will provide the core data for a wide range of investigations throughout the basin. The second network will provide specialized data set for part of the basin at a location that requires high resolution data. We also discuss research needs of remote sensing of rainfall that require additional specialized observational resources.

Enhanced WSR-88D Products. Using the Level II data from both radars it is possible to produce rainfall maps with the resolution of 1 km by 1 km over the watershed. As the range resolution of the two radars is 1 km, the azimuthal resolution (1 degree) translates to about 1.5 km at the 100 km range. However, since the WSR-88D radars do not scan on a fixed grid, the partial overlap of the two grids allows the higher resolution. We anticipate that the CUAHSI HIS would coordinate the algorithm development.

The radar rainfall observing system will be combined with a rain gauge network distributed in space. A set of rain gauges located on the line connecting the two WSR radars and spaced at about 20 km apart would provide information useful to both radars. As the basin is rather narrow and quite elongated in the direction connecting the two radars, the line runs near the center of the basin. Each gauge location will include two rain gauges of the same type.

We also propose to include in the network three multi-frequency profilers located at the radar sites and at the mid point between them. The configuration would provide each radar with a view of two profilers: one at the mid-range where bright band might be located in low clouds stratiform precipitation systems, and the second one at far range where bright band may occur in convective systems. Also, these profilers would be located at distances ranging from about 150 km to 230 km from other two WSR-88D radars looking over the basin. Disdrometers will be installed at the locations of the profilers to provide the profiler rain drop size distribution (DSD) estimation algorithms with ground based data to compare. Additional disdrometers will be installed at locations where soil erosion studies are conducted.

Additional double rain gauge platforms will be located at the locations of other major sensor suites. Also the existing rain gauges (e.g. from the EcoNet)

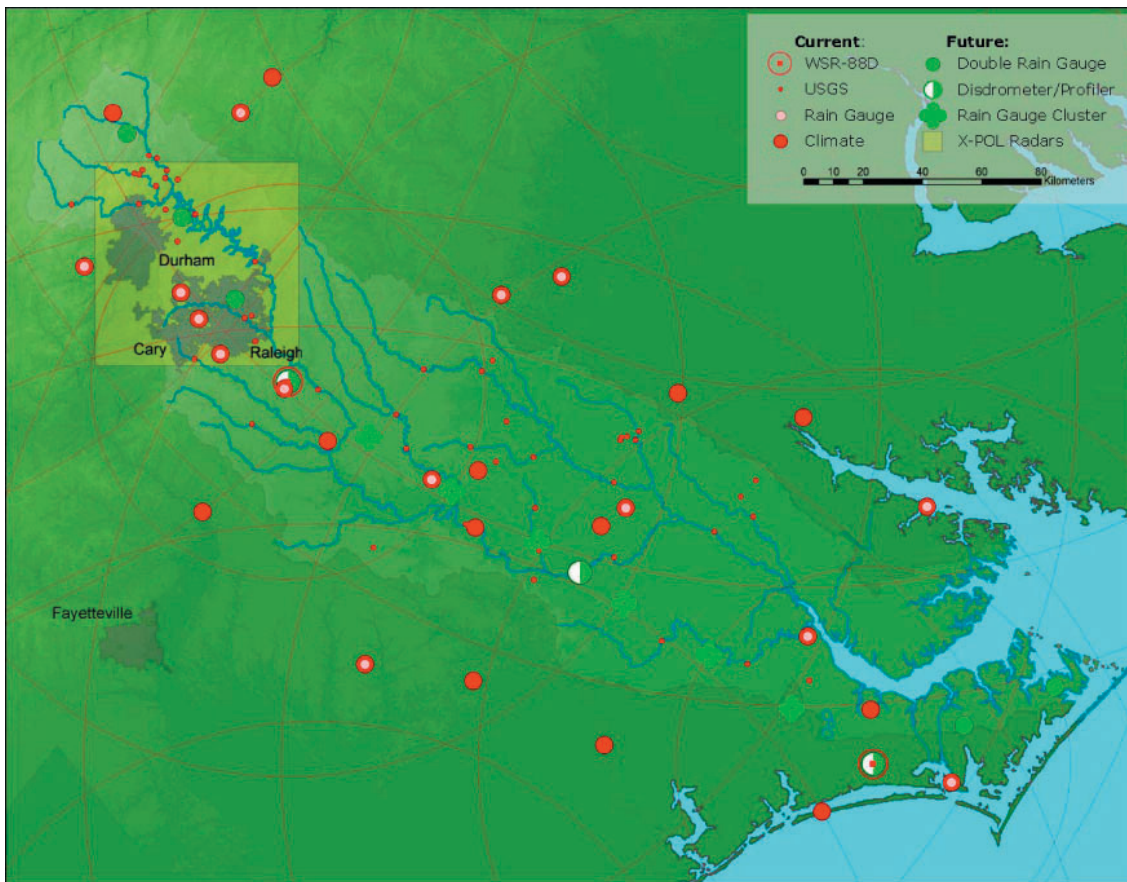


Figure 5.1. Rainfall observing network for the Neuse Watershed.

will be complemented with the second gauge. This configuration will provide fairly uniform sampling of surface rainfall throughout the basin at little additional cost. Also, in heavy forested areas there will be rain gauges installed at the top of the canopy.

The rain gauges we propose will be used either for making adjustments (calibration and corrections) to the radar-rainfall algorithms or for rainfall maps evaluation (validation) purposes. The gauges used for validation will not be used for calibration. We propose to locate the validation clusters along the range from the radars in the regions of radar overlap as well as in the western part of the basin. As radar and rain gauge sampling domains are vastly different even for the high-resolution radar produce we plan for the HOs, direct comparison of rain gauge and radar quantities presents a problem (Ciach and Krajewski 1999; Ciach et al. 2003; Habib et al. 2004). To mitigate the scale mismatch, we propose to construct a validation network which

will comprise a set of four double gauge platforms at a given 1 km pixel. This configuration reduces the sampling variance by over 90% with respect to a single gauge assuming exponential correlation function of rainfall with correlation distance of 5 km.

High-Resolution Radar Network. The network we described above will provide routine high-quality precipitation maps for a wide range of research investigation conducted using the HO data resources. However, as some of the studies may require higher resolution data, we propose to deploy a network of X-band polarimetric Doppler radars over a section of the basin. The network of four small radars will cover an area of about 500 km² and provide data with resolution of about 250 m. We propose to place this network (at least initially) over the urban area of Raleigh/Durham.

Specific Aspects of the Proposed Design. We propose combining four small radars into a synchronized network to provide multiple views of the same area. Rather than thinking of this as a collection of radars, we view the network as a single, albeit

distributed, instrument. The radars will be operated 24 hours a day, 7 days a week, as one instrument, optimized to provide high quality rainfall information. Our proposal is to use this paradigm and modify it for hydrologic research.

The facility should be able to meet the following needs:

1. Provide observations of near-surface rainfall with high spatial and temporal resolution. The spatial resolution should be about 200 m in range and 1.5° in azimuth which will permit generation of rainfall maps with Cartesian resolution on the order of 250×250 m or better. The radar's data acquisition and processing system should be capable of rapid scans so that temporal resolution of a volume scan is about 1–2 minutes.
2. Have a useful range of 20–30 km.
3. Have capability to measure enough rainfall-related parameters to remove most of the ambiguities associated with single parameter (i.e., reflectivity) estimation methods. This translates into the requirement that the radars operate at both horizontal and vertical polarization and measure several polarization diversity-based parameters with adequate accuracy. Polarimetric and Doppler data help to classify echo type, easily distinguishing rain from hail from snow and from other non-precipitating targets, thus leading to higher quality data.

By contrast, the radars that constitute the facility need not have all the capabilities of conventional meteorological radars. The following have a significant impact on reducing cost:

1. Full 360° azimuthal coverage is not needed but possible. Multiple radars will observe the same area, thus 90° azimuthal coverage is adequate.
2. Only precipitation measurements, close to the ground are needed, not atmospheric

studies, clear-air turbulence, etc. This has implications on the dynamic range and sensitivity—and thus the cost—of the receiver and signal processor.

3. High power is not required. It is true that X-band signals suffer attenuation, but the operating range is only 20–30 km, and there will be multiple views of the same area.
4. 5. Large antennas are not required. A 1.5° beamwidth equates to a 260-meter radar pixel width at 10 km. This meets our desired spatial resolution. At 10 GHz, a 1.5° or smaller beamwidth is easily attainable with a 6-ft parabolic antenna. Also a larger antenna, e.g. 9-ft, does not increase the cost that much.

Based on these considerations, we propose to design and build a network of small X-band, 25 kW peak power radars capable of processing both horizontal and vertical polarizations, and measuring the following: radar reflectivity at both polarizations, differential reflectivity, specific phase shift, differential phase shift, correlation coefficient of horizontal and vertical polarization signals, Doppler velocity, and its spectral width. The radars will be deployed and operated in around Raleigh/Durham area, collecting long-term, continuous data. Each radar will be mounted on a flatbed trailer equipped with hydraulic lifts that make it easy to deploy, to bring to CUAHSI Hydrologic Measurement Technology Facility for service, and so on. Thus constructing expensive towers or buildings on the leased land will not be required. Figure 5.1 provides an illustration of our conceptual design of the rainfall observing systems.

Specialized Validation Network. The Neuse Watershed as well as other CUAHSI HOs provides unprecedented opportunity to investigate fundamental question regarding uncertainty of radar and satellite remote sensing of precipitation methods. Krajewski and Smith (2002) discuss in detail the relevant research agenda. Here, we only point out that many basic questions remain unanswered. What is the probability distribution of radar-rainfall errors? Are the errors correlated in space and/or time? How do they depend on space/time scale? How do they

depend on local rainfall climatology? Arguably, answering these questions is more important for the future progress in hydrology than meteorology.

We propose to deploy a ground reference network that will be capable of addressing specific hypotheses regarding radar-rainfall uncertainties posed above. To address these issues requires a cluster of several gauges that would permit direct validation. With sufficient density of the rain gauges we should be able to estimate short-term rainfall accumulation with high accuracy. For example, Moore et al (2000) developed an optimal configuration for eight gauges sampling a 2 km by 2 km scale. Krajewski (2001) estimated that 17 rain gauges in the same size pixel will allow estimation of the ground reference with error less than 5% for most of the rainfall climatology of the country.

Another example is that of error correlation in space. This requires developing two or more clusters separated by a certain distance. We calculated that 1 km² pixels equipped with eight gauges configured as proposed by Moore et al. (2000) would provide sufficiently reliable data.

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6. Energy Budgets, Evapotranspiration, and Land Surface-Atmosphere Exchange

Land surface-atmosphere exchange of water and energy are fundamental to understanding and predicting the terrestrial water cycle of the Neuse Watershed (NW). Quantitative understanding of surface processes is also relevant to the study of vegetation growth, evapotranspiration, infiltration and recharge to the water table, and the transport of nutrients, chemicals, and environmental tracers. The land surface responds to weather at the time scales of minutes to days and to climate forcing at seasonal and longer time scales. The essential properties that control land surface processes are the physical, chemical, and biological soil and canopy conditions that together regulate water retention and conductance within the soil-vegetation-atmosphere continuum.

6.1 Land-Atmosphere Exchange

6.1.1 Key Science Questions

This section describes specific questions and hypotheses pertinent to the land-atmosphere exchange component of the Neuse Watershed study. The scientific questions deal primarily with how external (e.g. climate, weather, N-deposition) and internal (e.g. land cover conversion) perturbations within the Neuse Watershed affect the magnitude and variability of water and energy fluxes between the land and atmosphere. The scales of these perturbations (or disturbances) span several orders-of-magnitude in both time and space, requiring long-term sampling within the hydrologic observation. The past century has seen widespread abandonment of agricultural lands within the Neuse. The replacement of natural forests with managed short term rotation pine plantations (loblolly pine, longleaf pine, and eastern white pine) within the Neuse Watershed is mirroring similar trends within the entire Southeastern United States, where the managed pine forest area has increased by a factor of 30 from 1950 to 2000 and now represents some 20% of the entire Southeast forested area. Human induced changes, such as from deciduous to coniferous vegetation cover (i.e. distributing leaf cover into winter months), also pose implications to the annual structure of water and energy fluxes, while also increasing the risk of ice and drought

damage -- two phenomena that are expected to intensify within the Southeastern United States according to climate change scenarios. The timescale of droughts is on the order of 2 months (and more), but its impact on the structure (e.g. leaf area, stand development) and function (water vapor fluxes) can last for several years.

The observatory design must capture effects stemming from multi-scale disturbances that originate outside the basin (e.g. synoptic meteorology), and originate inside the basin (e.g. land use changes). The atmospheric variables overlaying the land surface reflect both the internal and external effects. Hence, a logical representation of atmospheric states and fluxes (as well as their variability) must be formulated in a manner that allows for rigorous decomposition into extrinsic and intrinsic causes. With this background information, three specific questions are proposed:

- a. How do climatic and weather perturbations, including extremes such as ice storms, droughts, and hurricanes affect the short and long-term fluctuations in water and energy fluxes between the land surface and the atmosphere for the key vegetation cover - soil type combinations? The "long-term scale" here must be sufficient to sample at least 20 years; the time scale used in current and projected forestry practices in the Southeast (e.g. the time scale used from seedlings to harvesting trees for wood).
- b. What is the impact of increased N deposition rate from the atmosphere on local and basin scale water and energy fluxes? Increases in leaf nitrogen are known to impact the maximum carboxylation capacity of C3 plants, which then impacts maximum stomatal conductance. Also, soil N regulates autotrophic carbon allocation to above (including foliage) and below ground.
- c. How well do top-down and bottom-up approaches reconstruct the spatial and

temporal variability of the NW water vapor and energy fluxes? Questions about the magnitude and dynamics of water vapor sources and sinks are at the center of scientific debate about global change. Most global, continental, and regional estimates of the water vapor balance follow a top-down inversion approach, using atmospheric transport models to relate measured differences in atmospheric water vapor concentration to the source/sink strength at the surface, by inverting the mass-conservation equation. However, source/sink estimates derived from inverse models have limited temporal and spatial resolutions, and are not able to consider biotic controls or human disturbances in isolation. Because inverse methods deliver little process-level information about the dynamics of individual components of the surface water balance, they cannot directly be used in future predictions. Nonetheless, they can provide an over-all measure of the regional-scale water and energy fluxes. In contrast, bottom-up (or forward approaches) aggregate source/sink information from small to large scales. Bottom-up strategies to estimate large-scale water balances thus retain some of the high-resolution process-level information of spatial and temporal source/sink dynamics such as the ones described in question 6.1.1. However, aggregating process-level information across a wide range of scales requires high resolution data of biophysical forcing over the entire domain, and comes at the expense of potentially large and unknown aggregation errors.

6.1.2 Observing Strategy

To address science question #1, eddy-correlation systems will be used to measure water and energy fluxes across a suite of the key soil-vegetation combinations within the Neuse Watershed. These measurements will be co-located with radiation component budget measurements and standard meteorological variables (see Table 6.1) within stream-gauged catchment areas. Canopy physiological and soil hydraulic properties will be sampled at time scales comparable to the

leaf area or litter dynamics (~1 month). These measurements could be aggregated to estimate the impacts for the particular cover distribution and the effect of land use/cover change scenarios on the resulting basin wide water and energy fluxes, but do not consider feedbacks from the atmospheric boundary layer (ABL). To account for these feedbacks, the local fluxes must be permitted to interact with the local atmospheric state (e.g. vapor pressure deficit or VPD) and the meso-scale weather system. Hence, a methodology that takes meso-scale air temperature and water vapor concentration measured from radiosondes (and gap-filled from NCEP) and “spatially downscales” them to an eddy-covariance tower footprint is required.

The NCEP regional scale estimates are 32 km in horizontal extent and set the boundary conditions above the ABL. These ABL upper boundary conditions are driven by large-scale weather patterns and not local fluxes from a given land cover. Standard ABL budget equations for heat and water vapor will be used to link surface fluxes and near surface atmospheric state variables to the ABL dynamics. To solve these budget equations, the velocity statistics (particularly, the mean wind speed profile and the vertical velocity standard deviation) must be known. These statistics will be measured using a network of SODAR stations co-located with clusters of eddy-covariance towers (see Table 6.3). The ABL budget equations will establish a dynamic coupling that permit the propagation of synoptic scale temporal variability due to changes in weather patterns to local atmospheric state variables and local fluxes (within the footprint of the eddy-covariance towers). In short, within a heterogeneous landscape mosaic composed of several land cover types, we do not expect VPD just above a bare soil surface to be identical to a neighboring patch of transpiring forest despite the fact that the mesoscale temperature and water vapor concentration (external forcing) are similar above both of those patches. Hence, when evaluating the effect of land use/cover change scenarios on the resulting basin wide water and energy fluxes, the local VPD and other state variables as well as the local energy and water fluxes in equilibrium with the local surface can be estimated from the mesoscale external forcing and the physiological, morphological, radiative, and soil hydraulic properties. To test the

spatial aggregation scheme (on short time scales), intensive field campaigns that include aircraft flux measurements will be conducted.

To address science question #2, wet and dry N deposition rates will be sampled in coordination with the precipitation network, and augmenting the regional NADP and CASTNET system. Leaf and soil nitrogen sampling will be used to complement the physiological and soil moisture measurements (see Table 6.2). From these measurements, we will relate shifts in N deposition to (intrinsic) changes in leaf-physiology, stomatal conductance, and leaf area, which in turn, can be related to water vapor fluxes and energy partitioning via standard physiological and eco-hydrological models.

To address science question #3, the NW observatory provides a unique possibility to develop a new strategy that combines several independent approaches for estimating water vapor exchange rates: in-situ soil moisture content, micrometeorological observations, atmospheric boundary layer and ecophysiology models, satellite observations, and ecosystem water-carbon exchange models. These independent approaches span across several orders of spatial and temporal scale, and cross-validating them at scales of overlap will be of fundamental value to the U.S. Global Water and Carbon Cycle science initiatives.

In the first two questions, several mechanistic features of the bottom-up scaling along with all the feed-backs for scales primarily influenced and exert influence on the ABL. For larger-scale integration, a remote sensing/ecosystem modeling approach (e.g., on-going activities using data from the MODIS instrument, with an eight-day composite period time-step) will be used and results will be compared to regional inverse modeling approaches at much coarser spatial and temporal resolutions. Remote sensing methods are described in Chapter 12.

6.2 Soil Moisture and Land Surface Processes

6.2.1 Key Science Questions

Soil moisture in the Neuse Watershed plays a key role in partitioning water and energy fluxes, and in providing moisture to the atmosphere for precipitation. It also controls patterns of groundwater recharge (Chapter 7). Specific to the

land-atmosphere, soil moisture storage provides an important memory of past atmospheric events and contributes to both positive and negative feedbacks in the atmosphere above and the deep soil and groundwater below. Here we describe key science questions, followed in the next section with description of a soil moisture observing system. The system is consistent with the other measurements discussed in this chapter and will be deployed in collocated monitoring suites.

- a. *How does soil moisture vary in space and time across the range of scales represented within the hydrologic observatory, and what are the contributions of atmospheric forcing, topography and soils?* Large-scale soil moisture variability is driven by space-time precipitation patterns, the radiative dynamics of the atmosphere. At local scales, land cover, soil conditions, and topography act to redistribute moisture. Soil moisture storage modulates precipitation, evaporation, transpiration, recharge and runoff response. Soil moisture, and its related fluxes, responds in a predictable manner to interannual variations in climate driven by ENSO, as well as seasonal, storm and weather events such as hurricane landfall, convective thunderstorm activity, and the absence of precipitation during drought. Temporal variations in soil moisture decrease with depth towards the water table, while residence times increases. Longer timescale atmospheric phenomena are recorded by progressively deeper soil water storage, with identifiable temporal lags.

Needed: a) A nested soil moisture monitoring network to make measurements across spatial scales. Components should include a regional soil moisture monitoring network to monitor large-scale patterns and capture precipitation gradients (roughly one site per 1000 km²; can be collocated to match the distribution of flux towers and ETR arrays described in Chapter 7); a monitoring site for each major land use/land cover class not captured by regional network (roughly 5 additional sites); and additional high resolution component(s) to characterize high frequency spatial variations, e.g.

hillslope-scale transects (1 site every 10 m for length of selected transect). b) Long-term soil moisture measurements at several depths in the soil profile (e.g. 5, 10, 20, 50, and 100 cm), down to the water table where feasible. These should be made at the regional (ETR) sites. Spatial density should be sufficient to capture the above and other climate forcing; the network described above should suffice. A remote sensing component of this investigation (Chapter 12) will make use of the nested sampling described here.

- b. *Are there observable feedbacks between soil moisture and mesoscale atmospheric processes (temperature, water vapor, clouds, precipitation) acting within the hydrologic observatories and surrounding regions?* Observatory-scale climate and weather results from a combination of large-scale forcing and regional-scale land-atmosphere interaction. Under certain conditions, surface wetness and its control over surface temperature and fluxes will have a detectable influence on mesoscale circulation and the formation of clouds and precipitation within the region. Additionally, evapotranspiration occurring within the boundaries of a hydrologic observatory can be an important source for precipitation within that region, and at larger, identifiable scales that include the observatory. Seasonal variations in precipitation recycling, within and surrounding the observatory, can be determined.

Needed: Energy flux (and boundary layer profile) measurements collocated with regional soil moisture network – same as outlined in 6.1. Mesoscale land-atmosphere modeling with assimilation capability.

- c. *What role does soil moisture play in ecological and biogeochemical processes in the NW, including the distribution and health of vegetation, vertical mass and energy exchange with the atmosphere, and lateral transport out of the observatory boundaries?* The pattern of water availability within and surrounding an observatory plays a critical role in determining the pattern of vegetation. Further, the time-stable

aspects of soil moisture variations (e.g. due to topographic and soil controls) which operate on a hierarchy of scales, are also important in dictating the various scales of vegetation variability. The spatial distribution of soil moisture is a central component of biogeochemical exchange with the atmosphere and carbon storage on land. Moisture availability is a key variable in photosynthetic processes and biological productivity. Hence carbon storage on land and the carbon dioxide flux to the atmosphere can both be linked to soil water availability. Trace gas fluxes (e.g. methane) may too depend in part in soil moisture content.

Needed: Energy flux (and boundary layer profile) measurements collocated with regional soil moisture network. Mesoscale land-atmosphere modeling with assimilation capability. Enhanced if necessary to capture major vegetation types and smaller-scale spatial variability. Regional and local-scale vegetation surveys. CO₂ flux monitoring collocated with soil moisture and energy flux measurements. Other trace gas measurements as desired. Regional-scale biomass monitoring, ground-based (e.g. FIA) or remote sensing (described in Chapter 12).

- d. *Have changes in land cover and land use significantly influenced the spatial-temporal distribution of soil water storage within the hydrologic observatory?* Historical changes in land use have significantly influenced water and energy balance partitioning at the land surface, including that of rainfall into infiltration and runoff, and of solar radiation into latent and sensible heat, and heat storage by the land surface. Consequently, patterns and amounts of soil water have been influenced, as have interactions with associated hydrological, ecological, biogeochemical, atmospheric and other Earth system processes.

Needed: Long-term soil moisture and flux monitoring as described above with additional sites added to characterize ongoing LULCC. Smaller-scale paired- or multi-watershed, single LULCC comparison studies.

6.2.2 Observing Strategy

Overall goals of the land-surface and soil moisture observing system are to characterize the observatory mean, variance, and spatial patterns of soil water and their continuous evolution in time. A broader goal is to enhance the understanding of soil moisture interactions with climate, weather, biogeochemistry and ecosystem dynamics. Measurements will be made at several depths into the soil profile (to the water table where feasible). Soil moisture monitoring sites will be collocated and built around tower and ETR arrays (see Chapter 7 for details about ETR arrays), for coordinated observation. The ETR arrays will be the sites of more intensive, profile measurements, with shallow soil moisture measurements sampled in more extensive transects by periodic survey.

The guiding vision for the proposed design is a network of instruments with sufficient density and appropriate placement so as to capture inherent spatial-temporal variability, including regional gradients and the importance of natural and human-induced land surface heterogeneity. Hence, a core, multiscale network is proposed to monitor moisture content at scales associated with regional precipitation gradients, land cover variations, soil heterogeneity and topographic variability. Such a network will also provide an important foundation for addressing the questions and hypotheses outlined above. In order to explore these research questions, site selection and instrument collocation will be critical (e.g. to address land use change impacts on soil water storage, or to characterize interactions with biogeochemical processes). It is anticipated that enhancements to this core measurement network, (e.g. for more detailed studies of scaling behavior or to increase spatial and temporal sampling frequencies) via supplemental instrumentation or intensive field campaigns, would be proposed by individual PIs through the competitive

funding process. For example, superconducting gravimeters could be installed in order to measure changes in total water storage, an integrated measure of overall basin wetness that would provide independent, complementary information to the soil moisture observations. It is important to note that the proposed soil moisture observing network will form the basis for monitoring long-term change, and it will provide key validation sites for satellite remote-sensing of soil moisture and water storage by sensors such as AMSR, SMOS, HYDROS and GRACE.

Soil moisture sensors will include TDR or other reliable technologies. Here we have selected the Hydra Probe, a capacitance probe manufactured by Stevens-Vitel, for consistency with the national network of USDA-NRCS Soil Climate Analysis Network (SCAN) sites. The proposed network will provide a picture of the spatial-temporal distribution of soil water that has not been previously possible. The resulting database will be invaluable to the research questions listed above, as well as to those to be pursued by many PIs in the Earth science community.

The suggested network design, which recognizes the inherent scales of soil moisture variation, will provide a natural framework for aggregating point measurements up to larger basin and regional scales. The concept of the hydrologic landscape (described earlier) can also play an important role in characterizing the scaling behavior of soil moisture, including aggregating point measurements up to larger scales. It is important to note that remote sensing will comprise an important component in the observing system that will provide a complementary spaceborne, large-scale perspective on basin-scale processes, as well as a critical framework for scaling point measurements to larger basin and regional scales.

7. Groundwater

Groundwater recharge is generally the most uncertain flux in the terrestrial water cycle and often the most difficult flux to estimate. Recharge is critical for assessing water resources because recharge replenishes aquifers and may transport contaminants from the land surface to underlying aquifers. The magnitude of groundwater discharge to streams and to the Neuse estuary also ultimately depends on recharge to the aquifers. Recharge is a complex function of climate, topography, vegetation, LU/LC, soil type, and geology. Land-atmosphere processes greatly affect recharge because they control partitioning of precipitation into ET, runoff, and infiltration. Understanding the effect of climate variability (at seasonal, interannual, decadal, and longer time scales) on groundwater recharge is important for management of water resources. The terrestrial biosphere plays an important role in regulating recharge by controlling the amount of water returned to the atmosphere through ET. Type of vegetation (e.g. trees, grasses, crops) and vegetation phenology also affect recharge. Historical changes in LU/LC associated with the replacement of natural ecosystems with agricultural ecosystems and later abandonment of agricultural ecosystems may have markedly altered recharge rates; however, quantitative information on linkages between LU/LC and recharge is limited. The impact of increasing urbanization and related impervious cover should also be considered. The distribution of soils and underlying geologic units are strongly linked in the Neuse basin and may exert fundamental controls on groundwater recharge. The water table in many areas of the Neuse Basin is sufficiently shallow (1 – 4 m depth) that it may affect recharge. The goal of the HO measurement and monitoring program is to determine spatiotemporal variability in recharge. Quantification of recharge rates relative to fundamental controlling parameters is essential for sustainable development of water resources to meet human and ecosystem needs within the context of climate variability and LU/LC change.

7.1 Key Science Questions

- a. *What is the role of atmospheric forcing (weather and climate) in controlling spatiotemporal variability of groundwater recharge and what feedbacks exist between subsurface hydrology and atmospheric forcing? Assessing the impact of atmospheric forcing on spatial variability in groundwater recharge would require*

estimating recharge along a climate gradient for representative LU/LC, soil, and geologic settings. The impact of atmospheric forcing on temporal variability in recharge depends on recharge rate and groundwater residence time. Temporal variability in atmospheric forcing at short timescales (seasonal, interannual) may only be important in areas of fairly high recharge rates and short groundwater residence times that may be typical of the Piedmont area. In contrast, temporal variability in climate at much longer timescales (up to millennia) may be important for very low recharge rates and long residence times that may be typical of deep confined aquifers in the coastal plain area. Groundwater development in these areas is more akin to groundwater mining because of the very long timescales required for recharge. This is important to consider when evaluating sustainable development of water resources. Understanding the role of short term climate variability on soil moisture and shallow groundwater is important for recharge assessment. Biospheric feedbacks should also be examined when assessing potential impacts of temporal variability in atmospheric forcing on groundwater recharge. For example, elevated precipitation related to El Nino Southern Oscillation should increase soil moisture that may result in enhanced biomass productivity that could negatively feed back on soil moisture by increasing ET and negate the impact of increased precipitation on recharge. The linkages between hydrology and ecology are emphasized in the emerging field of ecohydrology and are important when assessing potential impacts of climate variability on groundwater recharge. Most recharge studies focus on the impact of atmospheric forcing on subsurface flow and recharge; however, there may also be feedbacks from subsurface hydrology to atmospheric forcing. Upward flow in the vadose zone is common in semiarid and arid regions during the Holocene

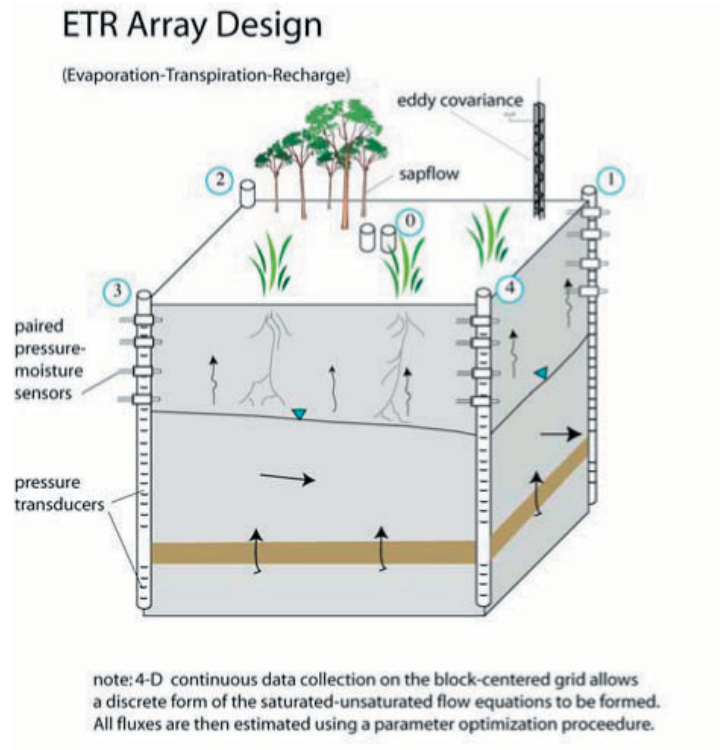


Fig. 7.1. ETR flux array for estimating recharge and evapotranspiration in the presence of a water table and loss or gain from deeper strata.

(Fischer, 1992; Andraski, 1997; Scanlon et al., 1994; Walvoord et al., 2002); however, upward flow may also occur in humid settings during dry periods and may affect regional weather and climate through precipitation recycling. An integrated, coherent measurement and monitoring approach will be required to assess linkages between variability in atmospheric forcing and groundwater recharge.

Needed: Recharge can be estimated using a variety of different approaches, including physical, chemical, isotopic, and modeling based on data from surface water, unsaturated zone, and groundwater (Scanlon et al., 2002). Most approaches cannot measure recharge directly but only provide estimates of recharge rate. However, recently developed unsaturated zone drain gauges can be used to measure downward

water fluxes through the unsaturated zone and provide a direct measure of recharge (Gee et al., 2002). These will be used in areas of the Neuse Basin where recharge rates are expected to be high and where soils are sandy. Water table fluctuations also provide direct evidence of groundwater recharge and will be used to estimate recharge in many areas of the basin (Healy and Cook, 2002). Pressure head data (i.e. matric potential data) in the unsaturated zone are required to determine the depth of the zero flux plane which separates zones of upward water movement (ET) from downward water movement (recharge). Matric potential can be measured using heat dissipations sensors or tensiometers, depending on the range of soil matric potentials. Soil moisture decreases above the zero flux plane can be equated to ET and soil moisture increases below

the zero flux plane can be equated to recharge. ET estimates from soil moisture data can be compared with those based on micrometeorological data (Eddy Covariance stations). Soil moisture sensors described in Chapter 6 for evaluating land atmosphere interactions will be extended to the water table for recharge estimation. The types of sensors that can extend to depths of 10 – 20 m include neutron probe access tubes and other borehole sensors. The combined measurements of soil moisture, matric potential, water table, and groundwater flow will be made in an ET-R (evapotranspiration-recharge) flux array and consisting of a network of these instruments on a grid to estimate vertical and lateral water fluxes. ET-R arrays will be collocated with Eddy Covariance micrometeorological stations and will be installed along a transect across the Neuse Basin in representative LU/LC, soil, and geologic settings, to evaluate climate variability on recharge. In addition, a superconducting gravimeter will be deployed at selected stations to monitor subsurface changes in total water storage in the system.

Vertical profiles of groundwater ages will also be used to estimate groundwater residence times and recharge rates using appropriate tracers such as $^3\text{H}/^3\text{He}$, CFCs, and SF_6 for young water (< 50 yr old) and ^{14}C for older water (Cook and Herczeg, 2000). Noble gases will be used to estimate the temperature and elevation at which recharge occurred. Baseflow discharge to streams will be used to provide a lower bound on recharge by assuming groundwater recharge equals groundwater discharge; however, this approach does not account for groundwater pumping, riparian ET, or movement of water to deeper aquifer systems. Physical and chemical hydrograph separation will be used to determine the baseflow component of surface water flow.

In addition to flux estimation, hydraulic parameters such as hydraulic conductivity and water retention functions for the unsaturated zone are required for modeling recharge. This information can be determined in part from online databases such as STATSGO and

SSURGO. However, HOs should supplement this information with sample collection in representative areas for measurement of hydraulic parameters.

Recharge will be estimated using the above approaches along a regional transect from the Piedmont to the Coastal Plain. The proposed measurement and monitoring network should include a nested system at the watershed scale. The nodes in the network should be chosen based on the characteristic hydrologic landscapes regions (HLR) in the Neuse watershed (Chapter 2). The sites should be collocated with the micrometeorologic and soil moisture monitoring stations described in Chapter 6. Hillslope scale transects will also be conducted in selected areas to characterize flow to nearby streams. Preliminary modeling will be conducted to estimate recharge using land atmosphere, unsaturated zone, or groundwater models. As data are being collected, the models will be used to synthesize the data and regionalize point recharge estimates.

- b. *How do land use/land cover changes affect recharge?* Humans have exerted large scale changes on terrestrial ecosystems through the last few centuries, primarily through agricultural activities. More recently, agricultural areas are being abandoned. Understanding the impacts of past and future LU/LC changes on the water cycle, particularly recharge, is critical for water resources management. Land use/land cover changes can modify many of the controlling parameters on recharge, such as precipitation, water application (irrigation), vegetation, and soils (e.g. tillage, impervious cover). Water application is greatly increased through irrigation and should markedly enhance recharge. Agricultural practices can also feed back to impact regional climate through precipitation recycling related to irrigated areas. Changes from natural to agricultural ecosystems alter many vegetation parameters that affect recharge, such as fractional vegetation coverage, leaf area index, and rooting depth. Fallow periods in agricultural rotations should increase recharge because there is no transpiration.

Unsaturated zones in semiarid and arid regions are often sufficiently thick to provide an archive of the impact of past LU/LC changes on recharge; however, vadose zones in humid regions are typically too thin. The impact of LU/LC changes on recharge can be evaluated by estimating recharge beneath current LU/LC and using space as a proxy for time. b. Linkages between ecology and hydrology need to be understood to better manage water resources. The emerging field of ecohydrology addresses these linkages (Rodriguez-Iturbe, 2000). Soil moisture is both the cause and the consequence of vegetation dynamics. Varying soil moisture strongly impacts the pattern and health of vegetation. Increased biomass production can negatively feedback to soil moisture and affect recharge resulting from soil moisture variability.

Needed: In order to evaluate the impact of LU/LC changes on recharge, we need to quantify recharge rates beneath representative LU/LC in the various settings from the Piedmont to the Coastal Plain. LU/LC settings should include natural ecosystems, forests, crops (irrigated and nonirrigated), pasture and other representative settings. Regional and local-scale LU/LC surveys will be necessary and this work will be accomplished in cooperation with the Remote Sensing initiative. Regional-scale biomass monitoring, ground-based or remote sensing, will be a major part of the Neuse Science Plan. The recharge estimation approaches described in the previous section will be applied to the LU/LC settings to relate recharge to LU/LC. Knowing current relationships between these LU/LC and recharge will allow assessment of the impact of future LU/LC changes on groundwater recharge, which is very important for water resources management.

- c. How can the Neuse hydrologic observatory provide useful information for developing management programs that ensure sustainable development of the groundwater resources in the Neuse Basin? Quantitative understanding of

the groundwater budget will provide critical information required to optimize groundwater management plans for sustainable groundwater development. "Groundwater sustainability is defined as development and use of ground water in a manner that can be maintained for an indefinite time without causing unacceptable environmental, economic, or social consequences" (Alley et al., 1999). Groundwater resources include both the quantity and quality of water. Understanding the partitioning of the water cycle among various components including groundwater inputs (recharge from precipitation, irrigation, land applications), outputs (groundwater ET, baseflow discharge to streams, springs, and estuaries, groundwater pumpage), and changes in groundwater storage will be required to manage water resources. It will also be important to assess fluxes of solutes, including nutrients such as nitrate and various contaminants from the land surface to underlying aquifers via recharge. Nitrate loading to the system varies with application amounts and approaches (fertilizer, manure, concentrated animal feeding operations etc) and recharge rate. Processes affecting nutrient levels in aquifers are also important, such as dilution and denitrification.

Needed: Improved quantification of groundwater recharge and understanding impacts of climate variability and LU/LC changes on recharge will be extremely useful in developing sustainable groundwater management plans. The processes for quantifying recharge are described in previous sections. Quantitative information on groundwater discharge is limited. The ET-R arrays will help quantify groundwater ET in different settings. Baseflow discharge to streams can be estimated using physical and chemical data. This will be facilitated by the expanded stream gauging network described Chapter 4. Quantitative information on groundwater pumpage is limited; however, this is a large flux that needs to be estimated. Because it will be impossible to meter

each well individually, innovative approaches will be required to provide estimates of this flux. The social sciences component of the HO program will be required to develop surveys to estimate groundwater pumpage for various uses including irrigation, municipal, and domestic purposes. The superconducting gravimeter can be used to estimate changes in water storage at different points. Because the gravimeter estimates total subsurface storage changes, soil moisture monitoring and groundwater level fluctuations will be used to determine if storage changes are occurring in the saturated or unsaturated zones. This newly developed instrument will be deployed in areas where soil moisture and water tables are being monitored and should remain at a site for at least a few months to equilibrate and to provide time series on water storage changes that can be related to precipitation, ET, and groundwater pumpage. Modeling is the only tool that can be used to predict water availability; therefore, groundwater models should be developed to optimize a groundwater management plan. The measurements and data being collected at the HO can be used as input to the models and provide information on boundary conditions. In addition, these data can also be used to calibrate the models. Intensive field campaigns will be required to develop synoptic water table maps for water availability studies. Head data, groundwater age data, baseflow discharge to streams all can be used for model calibration. Aquifer tests will be required to estimate hydraulic conductivity and storativity of the different geologic units. Modeling is also a valuable tool in synthesizing data and regionalizing point estimates of different fluxes. Although existing codes for simulating groundwater and surface water are limited and have many limitations, the ultimate goal would be to simulate the entire system that includes land-atmosphere, unsaturated and saturated zones, and surface water. Using this approach, groundwater discharge to streams can be simulated and the groundwater management plan can be designed to maintain instream flows for human and ecosystem needs. Transport

should also be included in the simulations and fluxes of nutrients such as nitrate and nonpoint source contaminants can also be evaluated using these simulations. This comprehensive modeling approach will allow water availability to be simulated as a function of climate variability and change, LU/LC change, groundwater pumpage and other factors. The Neuse HO will provide a unique data set to constrain these simulations.

7.2 Observing Strategy

7.2.1 Objectives & Goals

For the Neuse, the measurement or estimation of fluxes such as recharge and discharge (ET, baseflow to streams and estuaries, pumpage) and storages within reservoirs (e.g. vadose zone, saturated zone) represents an important challenge to the observing system design. The main objective of the design is the coherent deployment of sensors to “close” the water and energy budget using concurrent atmospheric, vadose zone, groundwater, and surface water sensor arrays such that 3-D fluxes of evapotranspiration, recharge, and groundwater discharge can be estimated. Towards this end we propose to design and deploy an integrated sensor system which measures states and fluxes within a 3-D volume. This volume contains the atmospheric zone above the land surface, the plant zone (canopy and roots), the vadose zone, and the shallow saturated zone. The goal of integrated and concurrent flux estimation is to improve our ability to close the water budget locally. This comprehensive monitoring system at representative locations will be supplemented with other approaches (e.g. drain gauges, age dating, baseflow discharge to streams).

7.2.2 The Subsurface Observing System

The observing system for soil moisture, recharge and groundwater flow is referred to as an ET-R flux array (evapotranspiration-recharge). The ET-R arrays, collocated with a micrometeorologic station for estimating ET (eddy covariance or Bowen ratio system) will allow local closure of the water and energy budget and improve estimates of vertical and lateral fluxes in the presence of a water table. Together the ET-R

array and micrometeorologic station will allow evaluation of the depth at which ET is occurring (e.g., saturated zone, shallow or deep vadose zone). Sap flow measurements in the vegetation will provide separate estimates of transpiration from different vegetation. The design of the vadose zone sensor spacings vertically is determined by placing the sensors deeper than the maximum depth of the “plane of zero flux,” the depth to which transient evapotranspiration penetrates (Shuttleworth, 1992). Because water table fluctuations are a function of vertical and lateral flow, the spacing of observation wells will be determined by the gradient of the water table and the sensitivity of the transducers. For example if the local slope of the water table is ~ 0.001 , then a spacing of 10 m is sufficient for transducers with accuracy of 1 mm. For deep water table settings (>20 m), the ET-R array may require additional soil moisture/pressure sensors placed vertically to assure that the zero flux plane can be identified. The arrays are designed and installed for the purpose of estimating all fluxes within a 3-D finite volume. The ET-R array can generate data to support a local application of Richards’ equation from the land surface to the water table. Figure 7.1 illustrates the arrays including collocated micrometeorologic stations (described in Chapter 6). Newly developed superconducting gravimeter will be evaluated to monitor changes in subsurface water storage at selected ET-R sites. The ET-R array provides the primary component of the monitoring system and will be deployed to evaluate the impacts of climate variability and LU/LC change on groundwater recharge.

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8. Groundwater Exchange

8.1 Key Science Questions

a. *What are the rates of groundwater discharge in the Neuse Estuary and how do they vary with time, space, and weather (rainfall, evaporation, storm frequency/intensity)?*

Needed: Rates of groundwater exchange at different spatial scales (local/regional/estuarine) collected, with weather data, over >2 years.

b. *Which aquifer(s) is the dominant groundwater source to the Neuse Estuary?*

Needed: Knowledge of where different geologic units intersect the bottom of the estuary, and measurements (physical and/or chemical) to separately estimate discharge from these units.

c. *What is the age of the groundwater discharging into the Neuse estuary?*

Needed: Age dating analyses carried out on groundwater samples collected beneath and around the estuary from several wells screened within the aquifers discharging to the estuary.

d. *What is the nutrient contribution associated with groundwater discharge? How does this compare to other point and non-point sources? Has this nutrient flux changed or will it in the near future? What geochemical transformations occur prior to discharge?*

Needed: Nutrient analyses on groundwater samples collected from (1) wells surrounding the estuary, and (2) samplers with high vertical spatial resolution in areas of significant groundwater discharge. Also, evaluation of land-use change over the period of time defined by the age of groundwater currently discharging.

e. *What is the role of subsurface paleochannels in controlling the spatial distribution of groundwater discharge to the Neuse Estuary?*

Needed: Data from previous and on-going investigations on the occurrence of large paleochannels identified by drilling and seismic imaging, together with data on groundwater discharge to the estuary.

f. *What role do variations in estuarine circulation play in the spatial distribution of groundwater discharge/recharge?*

Needed: Continued support of monitoring platforms currently active within the estuary,

and addition of 2-3 additional platforms, with all platforms monitoring at least salinity, temperature, dissolved oxygen, and current vectors in surface and bottom waters.

The most effective method to quantify groundwater discharge (and associated chemical inputs) to the Neuse Estuary is by integrating geochemical and hydrogeological techniques. Three independent methods for evaluating groundwater contributions and nutrient flux into the estuary should ultimately be employed: geochemical (local and regional scales), physical (discrete locations), and modeling (regional and watershed scales) approaches.

8.2 Observing Strategy

8.2.1 Geochemical Approach

Previous studies have shown that natural tracers (^{222}Rn , Ra isotopes) are able to detect areas of enhanced subsurface fluid discharge into coastal environments. Each of these natural tracers will be employed to quantify the groundwater contribution. By using more than a single tracer, there is the advantage of cross-checking groundwater flux estimates with independent methods. In addition, short-lived radium isotopes can also provide information concerning the sediment/water interface (particle re-suspension) and surface water processes.

Radon is typically elevated in groundwater due to the production and recoil processes originating from radium within the aquifer matrix, thus accumulating as a dissolved gas in the groundwater. Groundwater discharged into coastal waters will therefore have excess ^{222}Rn relative to its direct parent, ^{226}Ra . In the absence of external sources and sinks, secular equilibrium would exist between the two nuclides, due to the large differences in half-lives (3.8 days for ^{222}Rn , 1622 years for ^{226}Ra). The input of groundwater to coastal waters enriched in ^{222}Rn relative to ^{226}Ra will result in observed excess radon in the estuarine water column. This technique has been used to quantify the groundwater contribution in several coastal systems.

Radium has been shown to be a useful tracer of benthic disturbance and groundwater discharge. Radium has four isotopes with half-

lives ranging from 4 days to 1600 years (1622 years for ^{226}Ra , 5.75 years for ^{228}Ra , 3.66 days for ^{224}Ra , and 11.4 days for ^{223}Ra), making it a useful tracer on several timescales. Although radium is typically bound to particles in low ionic strength waters, it is effectively released upon mixing with marine waters and behaves nearly conservatively once released. Sources of radium to coastal waters include desorption from river-borne particles, sedimentary particle release, and groundwater discharge. If the first two components can be measured and the water residence time established, the Ra flux attributed to groundwater flow is attainable.

In order to evaluate the connection between groundwater inputs and surface water tracer inventories, a mass balance will be developed of all possible sources and sinks of these natural tracers. A simple box model for these tracers may be used to describe the source and sink terms in the Neuse Estuary. In general, the tracer inventory is a balance between: (1) benthic advective-diffusive exchange; (2) in situ production and loss, i.e. decay, desorption, adsorption, etc.; (3) horizontal water column advection; and (4) air-sea exchange. Benthic advective-diffusive exchange processes can be further divided into molecular diffusion, sediment irrigation and re-suspension, and fluid flow through the sediments.

A mass balance for the model may be constructed for ^{222}Rn :

$$V_s C_i A_o + J_{Ben} + J_{Resus} + (\lambda_{Rn} C_{Ra}) V_n - V_s C_f A_n - (\lambda_{Rn} C_{Rn}) V_n = \frac{dC_{Rn}}{dt}$$

where $J_{Ben} = J_{diff} + J_{advec} = \phi D_s \frac{dc}{dz} + \omega C_{pw}$ = diffusion + advection; J_{resus} = radon in the water column associated with re-suspension events; v_s is the low frequency (non-tidal) current flow moving through the study area; C_i represents the initial radon activity entering the box; A_o is the area of the initial side of the box; D_s is the effective wet sediment diffusion coefficient; $\frac{dc}{dz}$ is the concentration gradient in the porewaters; ω is the advective velocity; C_w is the tracer concentration in the porewaters; λ_{Rn} is the decay constant of ^{222}Rn ; $\lambda_{Rn} C_{Ra}$ and $\lambda_{Rn} C_{Rn}$ account for production and decay of radon in the water column,

respectively; V_n is the volume of water in the box (estuary); C_f is the radon activity in water horizontally exiting the box; and A_n is the area of the exit side of the box. A similar mass balance can be constructed for the radium isotopes. Most of these parameters are measured directly or easily calculated.

This approach assesses all flux terms and estimates the groundwater contribution by difference. Specifically, the groundwater tracer contribution can be evaluated by measurements of the tracer water column inventory, calculation of the total benthic flux required to support these inventories, and an independent assessment of the diffusive component of this flux. Horizontal transport will be assessed by evaluating river flow conditions during sampling (monitoring platforms) and collecting samples from sites throughout the salinity gradient of the estuary. The advective component can then be quantified by application of an advective-diffusion model and measuring groundwater and porewater tracer concentrations.

Groundwater discharge to the estuary will most likely vary as a function of water table elevation and river flow, both a function of rainfall. Therefore, a sampling design should cover at least 2 years during the wet and dry periods of each year. The sampling plan is devised to allow for the evaluation of spatio-temporal variability of the tracer in the water column. At least three estuarine "cruises" should be completed within several weeks (<4) of each other during wet and dry season of each year. This would allow evaluation of the temporal variation of the tracers and determine the time scale at which the system is at steady-state relative to the tracers. This will allow estimates of the groundwater contribution during the extreme flow regimes of the river and also provide information on any short-term variations.

Sampling stations located along approximately 10 cross-estuary transects will provide the necessary spatial coverage to evaluate regions of elevated groundwater interactions. Approximately 30-40 stations within the estuary will be established. Hydrographic measurements and samples for tracer analyses (surface and bottom waters) will be collected at each site. Water samples

for tracer/nutrient analyses will also need to be collected from groundwater wells within the watershed (see below). These groundwater samples will be collected quarterly for the first two years. Total number of analyses for each tracer will be approximately 1200 estuarine, 150 groundwater, and 400 porewater samples.

8.2.2. Physical Approach

The physical approach is intended to be used at two spatial scales: local (the bed of the estuary and strata within a few meters depth) and watershed (defined loosely at this point as the broader surrounding area relevant to estuarine groundwater inputs, in recognition of the fact that the watershed contributing groundwater input to the estuary is not identical to the watershed delineated on the basis of surface topography). On the watershed scale, water level measurements in wells located throughout the eastern portion of the Neuse watershed, around the estuary, will provide head data and groundwater samples for geochemical tracers to estimate the larger-scale picture of groundwater movement toward the estuary. In addition, these wells will be used to establish the age of the water in the region and the groundwater nutrient concentrations. Therefore it will be necessary to evaluate existing groundwater wells screened in the Castle Hayne, Yorktown, and surficial aquifers.

Although a local scale hydrogeologic approach is not necessary for overall groundwater discharge quantification, the design will provide an additional independent method for direct measurement of discharge in areas deemed important/significant and a mechanism for evaluating groundwater geochemical transformations prior to discharge. These local scale study areas around the estuary will include well fields of approximately 16 monitoring wells and piezometers. These wells will be installed in order to monitor the piezometric surface and to sample the surficial aquifer and shallow underlying aquifers interacting with porewaters within estuarine sediments at each location. The well field will contain both monitoring wells, constructed of 2 inch Schedule 40 PVC with slotted screens within the saturated zone, and multilevel sampling wells. Multilevel sampling wells consist of several ¼ inch polyethylene tubes

with nytex screens strapped to a PVC core at different depths. These multilevel samplers allow evaluation of vertical hydraulic and geochemical gradients.

In order to quantify and model groundwater/surface water exchange, hydraulic conductivity (including spatial variation) and hydraulic head gradients must be determined. Ground penetrating radar (GPR) will be used as possible in the upland area in order to evaluate the presence and persistence of shallow subsurface lithologic variations. GPR data will be verified via soil samples collected during well installation. Information collected from pump tests and tidally-induced water table fluctuations will be used to quantify hydraulic conductivity, specific yield, and other essential parameters needed in order to model the system accurately. Finally, hydraulic gradients at each site will be monitored continuously throughout the study using a network of self-logging pressure transducers installed in some of the monitoring wells. Collectively, these physical measurements will provide the necessary information to calculate local scale time-varying groundwater flows based on Darcy's law. The flow patterns, rates, and geochemical data can then be used to derive fluxes across the seabed based on mass conservation. Seepage meters will also be used to allow comparison of fluxes based on direct seepage collection with those estimated using the Darcian approach.

The regional/watershed wells should be identified (and if necessary, installed) early in the project. The number of new wells is dependent on the number of publicly available wells for monitoring water height and collecting groundwater samples. It is estimated that approximately 10 wells <50 meters below ground surface will need to be installed. Ideally, these wells would be equipped with a continuous water-level monitoring device which would reduce technician time. Water level in wells should be measured at least monthly during the first 2 years and at least quarterly thereafter. Local scale well fields will be constructed following the initial geochemical evaluation. This will provide some insight into areas of potentially higher groundwater discharge. Geochemical measurements from these sites will then coincide with estuarine sampling over the remaining period (~2 years).

8.2.3 Modeling Approach

The watershed hydrogeologic modeling can be built on earlier models for the system and constrained by data collected under the programs described above. Generally, a three-dimensional model of groundwater flow will be constructed for the study area. During year 1, the hydrogeologic data base for the coastal plain will be compiled and used to formulate the conceptual model of the groundwater flow system.

The finite element model FEFLOW could be used in this study. This commercially-available code has considerable flexibility in grid design, it can accommodate density-dependent groundwater flow, and it has excellent post-processing data capabilities, including the display of fluxes across domain boundaries. Consideration will need to be given to determining the relationship between the representative spatial scale of the geochemically-based estimates of groundwater discharge and that which can be produced using a regional/watershed-scale flow model.

Numerical modeling will be carried out as a three-phase investigation. Preliminary model simulations will be carried out to: (1) examine

from a theoretical perspective the potential influence of the Neuse Estuary stage on the magnitude and spatial/temporal variation in groundwater discharge. Second, using only the hydrogeologic data base, the flow model will be calibrated and the magnitude and spatial distribution of groundwater discharge in the estuary will be predicted. Estimates of groundwater discharge from the model will be compared to estimates derived from the geochemical and physical measurement programs. Discrepancies between model-based estimates and those derived using geochemical techniques will be examined in detail to understand their origin. In phase three of the model study, the groundwater model will be re-calibrated to develop a model structure constrained by the additional information that can be derived from geochemically-based estimates of groundwater discharge. Flux estimates provide particularly strong constraints in model inversions (e.g., Saiers et al. 2004).

8.3 References

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9. Water Quality

The many strong linkages between the hydrologic cycle and biogeochemical cycles are important for both practical and basic scientific reasons. The hydrologic occurrence and transport of carbon, major nutrients and certain contaminants represent important controls on the structure and function of the terrestrial and aquatic ecosystems that are components of the Neuse watershed. Along with land use change, long term changes in these ecosystems can have a feedback effect on hydrologic processes at the large watershed scale. Further, naturally-occurring or human-introduced solutes can serve as hydrologic tracers that help elucidate the movement of water through the hydrologic cycle and provide an approach that is complementary to physical hydrologic measurements. The Neuse HO should support research on the linkages between hydrologic and biogeochemical cycles in the Neuse watershed by: (1) linking the hydrologic data and analyses discussed earlier with collection of chemical data in groundwater and surface water of the HO (through original HO measurements and gathering data from others' chemical measurements), and (2) providing a basic interpretation of the data (e.g., computation of chemical fluxes at different spatial and temporal scales, such as the riverine flux of a chemical into the estuary). The chemical parameters that will be studied include (a) those needed for understanding the coupling between hydrologic and biogeochemical processes, (b) those potentially useful for characterizing hydrologic flow paths, and (c) basic water quality parameters that support both goals. Chemical species and water quality parameters of interest in the Neuse HO, roughly grouped into these three classes, are:

- cations^b: Na, K, Mg, Ca, Sr, Ba
- anions^b: Cl, SO₄, Si, S, HCO₃
- nitrogen^a: NO₃, NH₄, dissolved organic nitrogen, total dissolved nitrogen
- phosphorus^a: phosphate, total phosphorus
- carbon^a: dissolved inorganic carbon, dissolved organic carbon, total dissolved carbon

- other trace elements^a: Fe, Al, Mn, Zn, As, Pb, Cr, Cu, Se
- basic water quality^c: pH, conductivity, dissolved oxygen, temperature
- suspended solids^c
- chlorophyll a, b, c and accessory pigments^a (in reservoirs and estuary only)

The importance of specific chemical parameters will differ among HOs. Nitrogen is of particular significance in the Neuse and many other temperate watersheds. With the development of nitrogen fertilizers, the emission of nitrogen from combustion of fossil fuels, and changes in livestock management, nitrogen has become a major pollutant with significant ecosystem effects throughout North America. The detailed discussion given below of nitrogen in the Neuse HO will not be repeated for each chemical species of interest; much of the measurement strategy and reasoning are applicable to other chemical species, with modifications based on the different sources and biogeochemical behaviors of different species.

9.1 Nitrogen Sources: Key Science Questions

While it is an essential element for life, nitrogen is also a widespread pollutant with serious consequences for ecosystems and people. Human wastes and agricultural operations (farm animal wastes and fertilizer) are often major sources of nitrogen release to watersheds. This holds true in the Neuse watershed, with 1.35 million people, 2 million hogs, and 23% of total area (open water plus land) devoted to row crop agriculture (NCDENR 2002). Coupling basic nitrogen measurements to the rigorous measurement of the hydrologic cycle described earlier will allow the Neuse HO to support research on the linkages between water and nitrogen at multiple temporal and spatial scales.

The HO will collect and analyze data on nitrogen stores and fluxes (Figure 9.1) to quantify basic elements of nitrogen storage and transport in the Neuse watershed and to support PI-driven

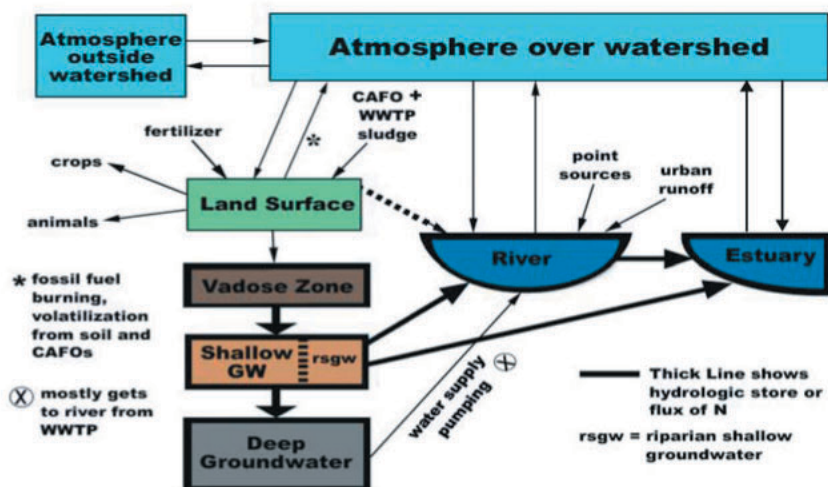


Figure 9.1. Simplified conceptual diagram of nitrogen storage and transport (not transformation) in the Neuse watershed, constructed as an aid to defining and designing the core activities in the area of nitrogen cycling for a Neuse HO. Thick lines indicate “hydrologic” stores and fluxes of nitrogen, thin lines “non-hydrologic” stores and fluxes.

research on linkages between hydrology and nitrogen in the HO. Core HO activities related to nitrogen will fall into two areas: original HO measurements and analysis of “hydrologic” nitrogen stores and fluxes (those that are a direct consequence of water storage and movement through the hydrologic cycle; Table 9.1), and gathering/analyzing data collected by others on non-hydrologic nitrogen stores and fluxes (Table 9.2).

Data collection related to hydrologic stores and fluxes of nitrogen will necessarily be closely coordinated with the hydrologic measurements themselves (e.g., nitrogen flux into the estuary from the Neuse River will be based on river discharge and nitrogen concentrations measured at the same place). In general, the estimate of each hydrologic nitrogen store will be based on the quantity of water and the aqueous nitrogen concentration in the store, and the estimate of each hydrologic nitrogen flux will be based on its volumetric water flow rate and aqueous nitrogen concentration. Nitrogen measurements will generally include nitrate+nitrite, ammonium, total dissolved nitrogen (TDN), and dissolved organic nitrogen (DON). Important gaseous species (N_2 and N_2O) will also be measured in groundwater samples (along with other gases) as an aid to interpreting recharge temperature and

denitrification in groundwater, and groundwater/surface water interactions.

Data on non-hydrologic stores and fluxes is available from a variety of academic, governmental, and other sources. HO staff will search out, obtain, archive, and interpret these data to the extent possible, as an aid in filling out a quantitative data base related to the stores and fluxes in Figure 1 and thereby supporting as broad a spectrum of PI-driven research as possible. These data are often available on a county basis; the HO will investigate techniques for adapting county-based data to the watershed boundary of the HO.

Data collection activities proposed for the HO will allow for at least preliminary answers to a number of basic questions regarding hydrologic storage and transport of nitrogen. These questions are broadly relevant; their answers, and comparison of those answers to analogous answers on other HOs, hold major promise for supporting individual PI-driven studies of hydrologic storage/transport of nitrogen. Many of the questions may hold well, with little modification, for other species that are significant for understanding biogeochemical or hydrologic processes (e.g., substitute carbon, phosphorus,

Hydrologic Store of Nitrogen	Hydrologic Flux of Nitrogen
<ul style="list-style-type: none"> • vadose zone • shallow groundwater • deep groundwater • rivers/streams • estuary 	<ul style="list-style-type: none"> • overland flow, land surface to rivers/streams • overland flow, land surface to estuary • infiltration, land surface to vadose zone • recharge, vadose zone to shallow groundwater • recharge, shallow to deep groundwater • shallow groundwater to rivers/streams • shallow groundwater to estuary • rivers/streams to estuary

Table 9.1. Hydrologic stores and fluxes of nitrogen.

Non-Hydrologic Store of Nitrogen	Non-Hydrologic Flux of Nitrogen
<ul style="list-style-type: none"> • plants (crops, forests) • solid organic matter in soil/sediments • animals (hogs, cattle, chickens, people) 	<ul style="list-style-type: none"> • atmospheric deposition • fertilizer applied to land • animal wastes applied to land • waste-water sludge applied to land • point-source discharges to rivers • animals imported/exported • crops imported/exported

Table 9.2. Non-hydrologic stores and fluxes of nitrogen.

selenium, etc., for “nitrogen”). Example questions (not intended as an exhaustive list) include:

- a. What are the hydrologic inputs of nitrogen to the Neuse estuary, via surface water and groundwater, from its watershed? What are the relative importance of rivers/streams, groundwater, and overland flow, and how do they compare to atmospheric deposition?
Needed: rates of groundwater input,

river/stream discharge, and overland flow into the estuary, together with nitrogen concentrations in these waters; also, an estimate of atmospheric deposition of nitrogen onto the estuary from other work (not an HO measurement).

- b. What is the variation in nitrogen transport with spatial scale along the Neuse River, from headwaters to coast? What are the main controls on this variation (point

- sources, land use, in-channel processing, groundwater inputs) and do they change with location/scale?
Needed: river/stream discharge and nitrogen concentration at different scales (small watershed to full Neuse River), together with data on the possible controls listed above, and a spatial analysis relating the controls to nitrogen transport.
- c. Are there major differences in nitrogen export from intermediate-size watersheds in the four different hydrologic zones (landscapes) of the Neuse (Upper and Lower Piedmont, Upper and Lower Coastal Plain)? Are there different relations between nitrogen export and watershed scale in the different zones, and if so why?
Needed: river/stream discharge data and nitrogen concentrations on the 17 intermediate-size watersheds (150-2600 km² in area) that make up >70% of the Neuse estuary watershed, at the outlets of the watersheds and also at different spatial scales within them; also, data on the possible controls listed in the previous question, and a spatial analysis relating the controls to nitrogen transport.
- d. How can information on nitrogen export from small watersheds with one dominant land use be used to estimate export from much larger watersheds of mixed land use?
Needed: data on stream discharge and nitrogen export from the small watersheds, and understanding of controls on those data, and a modeling analysis for scaling up.
- e. How much nitrogen is “lost” from the Neuse watershed via recharge to deep groundwater (e.g., groundwater in coastward-dipping Coastal Plain aquifers)?
Needed: rates of groundwater recharge to the deep groundwater systems, and nitrogen concentrations in the shallow groundwater that becomes recharge to the deep groundwater.
- f. What are the rates of nitrogen transport from groundwater to rivers/streams, and how do they vary with scale and other factors (geology, land use)?
Needed: rates of shallow groundwater discharge to rivers/streams at different scales (small stream to Neuse River) together with the nitrogen concentrations in the discharging groundwater; also, spatial analysis of relationships between groundwater-based nitrogen discharge and possible controls (geology, land use, etc.).
- g. What are the ages of groundwater currently discharging to rivers/streams? In this groundwater, is nitrogen concentration related to age? Does the age of groundwater and history of land use in the recharge area explain the range of nitrogen concentration in groundwaters currently discharging to rivers/streams, or is there also evidence that denitrification in groundwater plays a role?
Needed: groundwater ages (from CFC, SF₆, ³H/³He, or similar methods), nitrogen concentrations, and trace gas concentrations (including N₂ and noble gases); also, land and nitrogen use histories (from aerial photos and other records) in the recharge areas for the groundwater sampled.
- h. Given trends in nitrogen sources and data on relationships between nitrogen concentration and age in groundwater, what predictions can be made regarding the future of groundwater-based nitrogen discharge to the rivers/streams and the estuary? Is there a large body of high-nitrogen groundwater making its way through the subsurface to discharge into surface water? Or does it seem that subsurface denitrification is likely to prevent this?
Needed: data on the boundaries, flow rates, and nitrogen concentrations in groundwater systems across the watershed, together with information noted above for the previous question.
- i. What are the relative contributions of nitrate, ammonia, and DON to each of the

nitrogen fluxes mentioned above?
Needed: measurements of nitrate, ammonium, and DON in groundwater and surface water samples.

- j. Is there an important seasonal component (linked to temperature, hydrologic status, natural plant cycles, or agricultural operations) to answers to the questions above?

Needed: for the measurements discussed above, temporal coverage that spans all seasons and samples the variability within seasons (which for some fluxes may be large on time scales of several hours), together with data on the seasonal variations in temperature and the other potential influences listed in the question.

- k. What is the improvement in predictive performance (outside the calibration period) of watershed hydrologic/nutrient models when data on the nitrogen fluxes and stores described above is used in calibration?

Needed: predictions (outside the calibration period(s)) of nitrogen concentration or flux using an appropriate model, with the model calibrated both with and without the additional data on nitrogen store/flux.

9.2 Nitrogen Stores: Key Science Questions

9.2.1 Rivers/Streams

River and stream water will be continuously collected for analysis of nitrogen (nitrate, ammonium, DON, TDN) at the river/stream discharge measurement sites previously discussed in the hydrology section. Composite flow-proportional sampling will be used with discharge data for estimation of nitrogen flux at each site, and discrete grab samples will be used to investigate temporal dynamics in the concentrations of the different nitrogen species. More detail on a roving program of high-frequency (temporal) measurements is included in Section 9.6 below. The resultant knowledge of aqueous nitrogen concentrations in channels of different scale (from headwaters to the mouth of the Neuse River), together with knowledge of the volumes of water in the different channels (based

on stream/river stage measurements at gauging sites discussed in Chapter 4, and channel cross-sectional information derived from stream/river gauging activities and from geomorphologic measurements discussed in Chapter 10), provide the basis for estimating the quantity of dissolved nitrogen stored in rivers/streams. Different methods for interpolating concentrations between the point measurements at the gauging sites will be compared (e.g., a similar linear or other interpolation, an interpolation based on a more formal process model for nitrogen variation along a channel system, etc.). Methods will also be compared for interpolating between measurements of channel cross-sectional area (i.e., volume per unit length), in order to determine the needed channel volumes.

9.2.2 Vadose Zone

Water samples from the vadose zone will be collected at the same sites at which water content and other subsurface measurements are being made to quantify water stores and fluxes (Chapter 6). Data on nitrogen concentrations, together with water content and depth to water table (Chapter 6) will be used to quantify nitrogen storage in the vadose zone. Routine monthly water sample collection at these sites will be complemented with a roving program of higher-frequency measurements (daily or storm-event based during periods of one month to one year) that moves from site to site over the first five years (Section 9.3).

9.2.3 Shallow Groundwater, Deep Groundwater

Estimates of nitrogen storage in shallow groundwater (i.e., unconfined groundwater in near-surface soil and sedimentary deposits) and deep groundwater (i.e., confined groundwater not under water table conditions) will be based on: (1) measured nitrogen concentrations in groundwater, and (2) estimates of the volume of groundwater, based on the thickness, lateral extent, and porosity of the relevant porous media. Soil and hydrogeological information needed for the estimates of groundwater volume will be drawn from existing literature and databases. Concentration measurements will be made in the same wells discussed earlier with regard to measurement of head and hydrologic tracers (Chapter 6), and will thus span the full Neuse watershed and include all major combinations of

geology, topography, soil, and land use. Estimates of these shallow and deep groundwater stores will be refined as data on the relationship between groundwater age and nitrogen concentration become available; this information provides a basis for understanding the longitudinal variation in nitrogen along flowpaths in groundwater systems, and should improve early estimates of these two stores that are based only on their volumes and simple averaging of concentrations.

9.2.4 Estuary

The quantity of dissolved nitrogen in the Neuse estuary will be estimated from the volume of water (well-known from existing bathymetric data) and a program of water quality sampling similar to that of the recent MODMON project involving UNC-Chapel Hill, UNC-Charlotte, NCSU, ECU, Duke, National Marine Fisheries, NCDENR, the U.S. Geological Survey, and Weyerhaeuser Corporation (<http://www.marine.unc.edu/neuse/modmon/>). This study produced abundant data (<http://www.marine.unc.edu/neuse/modmon/results/results.htm>) and a good understanding of the spatial and temporal dynamics of water quality in the Neuse estuary, based on collecting and interpreting data at a number of sites in the estuary (<http://www.marine.unc.edu/neuse/modmon/monitor/wq/wqstation.htm>).

9.3 Observing Strategy

9.3.1 River/Stream Input to the Estuary

The rate of nitrogen input to the estuary via rivers and streams will be based on measurements of discharge and nitrogen concentration at the mouths of the three largest rivers that discharge directly to the estuary (Neuse River, Trent River, and Swift Creek) and the 4-5 largest of the small tidal creeks that discharge directly to the estuary. The discharge measurements are discussed in Chapter 4. Nitrogen discharge from the 4-5 largest tidal creeks will be extrapolated to the other smaller tidal creeks to estimate nitrogen output from the latter. Different approaches to this extrapolation will be compared, e.g.: (1) a simple regression of nitrogen output against watershed area, a land use index, and/or nitrogen use (many of these areas are farmed), or (2) a process-based watershed model of nitrogen export calibrated on the 4-5 monitored tidal watersheds and subsequently applied to

predict output from the others.

9.3.2 Shallow Groundwater Input to the Estuary

As discussed in Chapter 8, shallow groundwater input to the estuary will be estimated with an approach combining naturally-occurring tracers, physical hydrologic measurements, and modeling. The groundwater input information derived from this work will be combined with data on nitrogen concentrations in groundwater beneath the estuary to estimate the groundwater-based nitrogen input to the estuary. Groundwater samples for nitrogen analysis will be collected from the wells discussed in Chapter 8. Given the commonly-observed decrease in groundwater seepage rate with distance from shore in lakes and coastal waters, the nitrogen concentrations in groundwater seepage closer to shore will likely carry the greatest weight. HO staff will explore different analytical frameworks for estimation of this flux from the data, for example, use of a calibrated groundwater flow model (Chapter 8) and spatially-interpolated (kriged) nitrogen concentrations, versus use of the “whole-estuary” groundwater input based on ^{222}Rn (Chapter 8) with mean nitrogen concentrations (for each nitrogen species) in the near-estuary groundwater, perhaps with concentration at each well weighted by a physical estimate of seepage flux at the well.

9.3.3 Shallow Groundwater Input to Rivers/Streams

This nitrogen flux is distributed throughout the watershed wherever there are channels and is likely to vary considerably in space and time. At least two approaches will be taken (there may be others) to estimating groundwater-based nitrogen input to rivers/streams.

A “Darcian” approach to estimating groundwater exchange with rivers and streams of different size will be taken, drawing on subsurface physical hydrologic measurements discussed earlier (Chapter 6) and measured nitrogen concentrations in groundwater. Exchange rates will be based on head values measured in rivers/streams and in adjacent groundwater piezometers. Nitrogen concentrations will be measured in the same piezometers, and concentrations at a given location will be multiplied by seepage rate at the same location to give a rate of groundwater-based nitrogen exchange (almost certainly an input but

possibly an output at some places/times) with the river or stream.

An alternate approach that gives a groundwater exchange over a larger spatial scale than the Darcian approach is the channel mass balance approach. In this approach the net groundwater input to a section (reach) of channel would be determined from the water budget of the reach by measuring inflow at the upstream end, outflow at the downstream end, and any other inputs or outputs that are not groundwater. This approach is simplest to apply when it is not raining, so that storm-event processes like overland flow and shallow perched interflow are not operating. In that case, the only other potential water inputs are from tributaries and human point sources (e.g., NPDES permitted discharges). If these two sources are negligible or can be accounted for with data, net groundwater input to the reach can be determined. This quantity can be multiplied by the nitrogen concentration of groundwater (from near-channel groundwater samples) to give the groundwater-based nitrogen input to the channel reach. Benefits of the approach are that it covers a larger scale than the local small-scale Darcian calculation and also does not require hydraulic conductivity values. Drawbacks are that the channel mass balance for water may be too complex to know with accuracy during storms, and that the reach must be long enough to capture significant groundwater input so that the uncertainty in this input is small enough to make the result useful.

9.3.4 Intensive Field Campaigns

In order to interpret the results of the long term program quantifying the fluxes and stores of nitrogen in the Neuse, the HO will conduct a program of intensive field campaigns that will focus on hydrologic and biogeochemical processes that are hypothesized to influence the magnitude of these fluxes and stores but would not be well-studied with water quality data collected as outlined above. This work will use temporally and/or spatially intensive sampling in conjunction with tracer experiments as appropriate. These studies will be conducted at sites or river reaches that are representative of hydrologic zones in the Neuse and will focus, at least initially, on the Neuse River and six intensively-gauged intermediate-size watersheds

discussed in Chapter 4. These intensive sampling programs will be conducted at different sites from year to year and will be designed to answer specific questions (e.g., to quantify the short-time-scale dynamics of a particular nitrogen flux in different locations of the watershed having different geology, land use, topography, etc.). The specific questions will fall within the scope of the questions being addressed by the overall program, as highlighted below. For the Neuse watershed, the role of storms events of varying magnitude in mobilizing nitrogen is an important focus for these intensive studies. Other processes focused on by these intensive field campaigns are groundwater exchange with surface water and biogeochemical transformations in groundwater and in extensive riverine wetlands.

Example questions presented below are intended to complement the interpretation of the data acquired by the HO to address the overall questions posed under section 9.3. The coordination of the intensive field campaigns with the overall questions is important in the implementation of the HO, as the number of possibly interesting intensive studies would otherwise be unconstrained. Questions related to intensive field campaigns include:

- a. How do storm events accelerate the transport of nitrogen from the different stores in the Neuse watershed? Is there an increase in nitrogen transport that is caused by increasing the flux from stores that are not as hydrologically connected under baseflow conditions?

Needed: a program of high-frequency sampling at a few closely spaced sites in each of the four hydrologic zones conducted during storm events in summer, in order to document temporal dynamics in the concentrations of important nitrogen species. Comparable intensive sampling will be conducted at the same sites during baseflow. The scheduling of these intensive measurements will utilize the meteorological data available within the HO. For smaller reaches, these intensive sampling efforts may be augmented by injection of conservative tracers in order to quantify changes in flow and hyporheic exchange in different reaches during

storm events. These studies will address the question of **stream/river inputs of nitrogen to the Neuse estuary**.

- b. How do seasonal changes in ecosystems and agricultural lands influence the transport of nitrogen during storm events? **Needed:** studies of response to storm events in one or two streams during storm events in summer and in winter (or season of most stable hydrologic conditions) and comparable studies of variability in stable conditions. These studies will address the question of the **seasonal component of nitrogen inputs** associated with storm events.
- c. How do biogeochemical processes (e.g. denitrification) occurring in the hyporheic zone and riparian wetlands modulate the fluxes of nitrogen from groundwater to surface water in the Neuse watershed? Are these biogeochemical processes most important in the low order streams or in higher order reaches of the Neuse River? **Needed:** intensive studies that determine rates of denitrification at the stream and river reach scale. In low order streams, these studies will employ conservative tracers, addition of isotopically-enriched nitrogen and reactive transport modeling to determine first order rates for denitrification, comparable to the current LTER Nitex program. In higher order reaches, these studies will employ natural conservative tracers and biogeochemical rate measurements in riparian sediments. These studies will address the question of **denitrification in stream and riverine reaches** of the Neuse.
- d. Within a given stream reach, how spatially variable is the groundwater input of nitrogen and do the nitrogen inputs vary with the age of the groundwater entering within a reach? Does spatial variability in nitrogen content and age of groundwater scale with the magnitude of the stream or river segment? **Needed:** intensive studies, possibly employing conservative tracers, to determine the variability of groundwater inflows within the stream reaches of the

four hydrologic zones. These studies could be conducted following the first round of intensive studies conducted to assess the importance of storm events. These studies will address the question of **rates of groundwater transport from groundwater to rivers/streams and the dependence on scale, geology and land use**.

- e. What is the role of denitrification in groundwater as a sink for nitrogen in the Neuse? Is the rate of denitrification first order with respect to the groundwater nitrate concentration in aquifers, or is the rate controlled by the availability of electron donors, such as dissolved organic material, and therefore variable among hydrologic zones? **Needed:** studies of rates of denitrification in nested groundwater sites from the four hydrologic zones, with ancillary data on the concentrations of electron donors and flow rates within the local aquifer. These studies will address the question of the importance of **denitrification in ground waters** in mitigating nitrogen enrichment.

Many of the studies to be conducted as intensive field campaigns would employ similar methodologies and field sampling equipment, which would reduce their cost as they will be conducted sequentially over several years. An important tool will be the use of in-situ sensors and analyzers with telemetry capability. These sensors can be deployed initially as part of an intensive campaign and then incorporated on a more routine basis into the monitoring program as the reliability of the technology develops. Further, these intensive campaigns would be restricted in number (e.g., 2-3 per summer or winter season). The priority of particular intensive field campaigns can be assessed annually based on emerging questions from the monitoring program and previous intensive studies.

9.3 Reference

NCDENR. 2002. Neuse River Basinwide Water Quality Plan, Chapter 2: Neuse River Basin Overview, <http://h2o.enr.state.nc.us/basinwide/Neuse/2002/plan.htm>. North Carolina Department of Environment and Natural Resources, Water Resources Division, Raleigh, NC.

10. Sediment Transport and Geomorphology

Hydrologic processes strongly influence the transport of sediment within a river network and its long-term evolution. There are also strong linkages between sediment transport and water quality because nutrients and contaminants sorbed onto sediments may be eventually released to the water column. Furthermore, the deposition of sediment in coastal zones can strongly influence coastal primary productivity and the sustainability of marine resources, such as coral reefs. The geomorphology and patterns of sediment transport of the Neuse Watershed reflect its location in the Piedmont/coastal plain of North Carolina and proximity to the Atlantic Ocean. Important characteristics of the Neuse Watershed with respect to soil erosion and sediment transport are:

1. Extensive agricultural development since the 1600s resulted in significant soil erosion and sedimentation of the regional stream system. Agricultural abandonment over the last century may have significantly decreased primary soil erosion, although significant localized sediment sources still exist in urbanizing areas.
2. The area is frequently impacted by extreme rainfall from both convection and tropical storms and hurricanes. These events may result in mobilization of new upland sediment, but more significantly may remobilize sediment in alluvial stores deposited over the last 300 years.
3. The drainage network is extensively engineered at different scales. Urban development and intensive agriculture have lead to conditions that are very different from those that produced the drainage network. Channels have been straightened, lined, and re-routed, and drainage ditching and urban stormwater infrastructure are important components of the low order drainage network. Numerous small ponds exist in urban and agricultural regions and act as local sediment sinks. The Falls Dam hydraulically isolates the upper basin from the rest of the watershed.

The Piedmont presents an interesting example of dynamic landscape evolution with large space- and time-scale erosion processes. In contrast, the coastal plain is populated by low energy reaches and numerous extensive wetlands. Significant stores of carbon-bound nutrients may exist in sediment deposits. Episodic flushing due to extreme events may flush these deposits, enhancing nutrient transport. Other important influences are the extensive agricultural areas, a major urban area, and significant wooded lands. Thus, the Neuse River and the majority of its tributaries are not in equilibrium.

The design of the geomorphological measurements of the Neuse River observatory is based upon the existing characterization of the watershed, as described in detail in Chapter 3:

1. The Neuse Watershed has a very high-quality, spot-verified, recent land-cover data set, developed by USEPA.
2. There are a set of instrumented sub-catchments in the Contentnea Creek basin, the Upper Neuse, the Centennial Campus of North Carolina State University and the Open Grounds Farm in Cartaret County with drainage areas from 10ha. to 1248 km². These basins have been used in studies of increasing urbanization, changing farming practices, and climatic change (Johnson, 2001), forest hydrology, and row crop agriculture. Existing nested basins provide a seed for planning additional network augmentation to study scale effects.
3. An existing LIDAR dataset of the Neuse Watershed was created in response to extensive flooding by Hurricane Floyd. As the dataset is part of a coverage for the full state of North Carolina, resolution is not optimal for studying small scale (e.g. channel form) features, although the dataset provides a DEM significantly more accurate than standardly available USGS DEM.

10.1 Key Science Questions

Data collection activities proposed for the HO will address a set of basic questions regarding processes controlling sediment transport at the scale of small and large watersheds. Comparisons among watersheds with differing climatic and hydrologic regimes are likely to improve understanding of current modification and evolution of river networks, as well as the geomorphological effects of reservoirs. The questions offered below provide a framework for establishing research infrastructure needs that can be extended to address additional research questions.

a. *What is the time/space distribution of sediment sources (upland and alluvial) within the watershed at multiple scales (hillslopes: 10^0 km², catchments: 10^1 km², subwatersheds: 10^2 - 10^3 km², and full watershed)?* For the Neuse Watershed, a leading hypothesis is that current sediment sources are dominated by alluvial material derived from agriculture derived sedimentation accumulated over the past three centuries. **Hypothesis:** Agriculture derived alluvial sediment stores are the dominant source of fine grained sediment transported within the Neuse River basin, and provide sufficient supply to produce transport limited conditions. **Needed:** (1) measurements of sediment budget components in stratified sample of reaches, including: measurement of suspended and bedload at upper and lower boundary of sampled reaches (stratified by stream order/hydrologic landscape); (2) high resolution terrestrial survey of channel form and floodplain in the reach as series of cross sections and periodic resurvey; (3) erosion/deposition pins in floodplain/channel cross sections; (4) cosmogenic isotope/mineral sourcing of stream suspended and bed load to recent surface sediment or re-excavation of buried alluvial material; (5) analysis of floodplain cores with radiocarbon, cesmium 137 dating to identify shifts in sediment load and correlate with LU/LC change in watershed and mineralogy to provide source location.

b. *What are the interactions of the drainage network structure (topology, hydraulic geometry) as modified by urban and agricultural drainage infrastructure, with the routing, storage and residence time of water, sediment and nutrients within the watershed and particularly within alluvial areas?* **Hypothesis:** In the Neuse Watershed, recent efforts to extend and improve drainage efficiency of low

order channel networks (e.g. channel straightening, ditching, storm sewers) have promoted net erosion in lower order streams and alluviation in higher order channels.

Needed: studies of subcatchments in similar hydrologic landscapes with different degrees of channel "improvement." These can comprise a set of the instrumented catchments/reaches on which continuous flow and sediment rating curves are developed.

c. *Do heterogeneous channel environments promote greater retention and storage of carbon, nutrients and sediments (and bio-uptake of nutrients like nitrates and phosphorous). How does the retention in and mobilization of sediment from riparian wetlands and floodplains impact hydrologic budgets and the budgets of carbon, nitrogen and contaminants?* **Needed:** Local sampling of inflows/outflows in riparian zones and sediment core analysis in riparian wetlands and floodplains before and after major storm events. Measures of network complexity (planform sinuosity) and channel complexity (backwater areas, side channels, large woody debris) in concert with nutrient, water and sediment budgets.

d. *What is the magnitude and frequency of effective sediment and nutrient loading and transport within the NRB and their effects on the structuring of aquatic ecosystem function? Is there a dominant event in terms of aquatic ecosystem function? What are the relaxation times of aquatic systems to different magnitudes of hydrogeomorphic event?* **Hypothesis:** Periodic hurricanes are the dominant disturbance in structuring sediment and nutrient loading, pools and trophic structures in the lower river and estuary. **Needed:** Characterization of sedimentary system structure and composition to assess total loading of sediment and organic material to estuarine system.

e. *To what extent are fluvial networks are out of equilibrium with respect to sediment budgets and morphologic adjustment to sediment and flow regimes? Following major disturbances, channel form on a set of reaches may adjust to a new state or show long term transience.* **Hypothesis:** The current drainage network is in a period of transient adjustment to rapid changes in sediment load, flow regime and engineered drainage systems that have occurred over the past three centuries **Needed:** LIDAR surveys of selected reaches

following major events and investigation of long term changes achieved by LIDAR sampling of full channel planform, and cross-sections at log-stepped time intervals following major events.

10.2 Observing Strategy

The following sections outline new observational technologies that can be brought to bear in research of the science questions. While the traditional geomorphological tools and techniques are not emphasized, they are not dismissed. The focus of this development is on identification of new technological infrastructure to enable collection of consistent, observatory-wide data. The design committee has deliberately intended to use technology to the maximum degree possible to minimize labor and produce data of maximum uniformity throughout the observatory. Sites will be co-located with in-stream and hillslope monitoring discussed in ch.4 (surface water flow and overland flow).

10.2.1 Lidar Surveys

LIDAR data in the Upper Neuse River Basin are being evaluated. The quality and suitability for hydrology related research is mixed so a new survey using the latest LIDAR technology is quite important. It is likely that the price for LIDAR surveys will go down over time and if the surveys are coordinated with NC Flood program a new complete survey can be done every 5 years. Fly mainstems with high resolution LIDAR, sample tributaries according to "hydrologic landscape" categories for paired basins, down to first order streams. Some regular resurveying to track long term changes of channel form (in regard to channel equilibrium question) as well as log-spaced re-measurement time intervals after large events to track relaxation time, or if the channel returns to predisturbance form. Plan for a complete new LIDAR survey of the entire watershed in 2005 or 2006 in close collaboration with the NC Flood mapping program. The last survey was in 2001 and there were some plans to do the surveys in 5 year intervals.

10.2.2 Characterization of Channel Form at High Resolution: Bed Morphology, Bedforms, Bed, and Bank Materials

Towed sonar is useful for observing bed morphology in larger channels. Smaller study

reaches require surveying using total stations or possibly laser scanners or airborne lidar during exceptionally low-flow periods. Bed sediment sampling will be performed periodically and following major events by coring storage. These data will show burial and exhumation of particulate organics, and enable determination of nutrient forms.

Multibeam sonar bathymetry data from small research boats have high accuracy. This technology will be used together with simultaneous surveys of channel banks using a laser scanner in the monitored reaches annually and after major events. These data will provide unique insight into the channel evolution and response to major events. An example of multibeam bathymetry data showing underwater mound flattening can be seen at: <http://skagit.meas.ncsu.edu/~helena/measwork/mound/mound.html>

We can estimate anthropomorphic inputs of carbon, water, nutrients by a systematic campaign of stormwater sampling (or ditch/tile drain sampling) during a variety of storm events and during different seasons to develop estimates to assign to catchments of varying land use. This can be done with permanently deployed stormwater sampling devices that will require manual collection after an event. This sampling strategy might be an essential component of paired basin studies.

10.2.3 Real Time Suspended Sediment Sampling

New light diffusion techniques are workable in laboratory settings. High concentrations of suspended sediment require dilution, but particle size distribution measurements are possible using laser diffraction (e.g. Beckman Coulter) devices. This technology is not yet ready for field deployment and is restricted to laboratory use. Development of field deployable devices is an important need that will be coordinated with the HMF. The use of turbidity as a surrogate for suspended sediment concentration measurements is possible in combination with inter-event sampling for calibration. The question of sample representativeness impedes automated sampling in larger cross-sections. Periodic measurements of suspended sediment concentration using traditional laboratory techniques, combined with

a Kalman filter approach applied to turbidity data may lead to continuous suspended sediment concentration estimates of known uncertainty.

10.2.4 Bed Load Transport Sampling

Bed load measurement remains problematic, and highly uncertain. Changes in in-channel storage can be observed in larger cross-sections using towed sonar or lidar at low water levels. It is useful to plan for a pre- and post flood surveys of the floodplain areas where most changes could be expected. These surveys would be accomplished using LIDAR measurements from lower altitudes, collected more accurately than LIDAR surveys of the entire watershed. Planning and budgeting is complicated because we cannot plan a flood event but if there is funding and infrastructure set aside, similar pre- and post-event surveys are possible. This was done along the North Carolina coast in the aftermath of Hurricane Isabel with a sequence of post disturbance surveys. This type of survey would be most useful for Neuse River main stem and its floodplain.

In smaller streams, ground-based laser-scanner technology may be best for surveying the streams, assessing bank erosion and monitoring the study reaches. Note that these scanners do not penetrate dense vegetation; they actually scan the branches and leaves on the trees etc. However, this technology is much more suitable for streams than airborne LIDAR in smaller channels. The new scanners are getting lighter and cheaper, costing around \$80,000. Bed load instrumentation that should be considered include: radio frequency identification (RFID) tags on tracer clasts, impact meters that count particles as they impact a sensor surface, pass-through particle counters using lasers, and perhaps underwater particle image velocimetry.

10.2.5 Hillslope and field scale observations of flow, erosion, and deposition

Spatially distributed erosion and deposition could be measured by ground based laser scanner at least for an area that is bare or has limited vegetation. This would allow assessment of the quantities of sediment from the hillslopes that reach the stream and how much is deposited downslope. This research will use ISCO type samplers in conjunction with overland flow

magnitude and frequency studies (4.2) to estimate hillslope scale mobilization and transport, only requiring marginal cost of sediment concentration analysis in collected runoff.

10.2.6 Design Elements for sediment transport measurements

Given the unique conditions that exist in the Neuse River Basin, the candidate set of science questions, and the discussion of available technology and sampling strategies, the following specific design elements are proposed:

1. Study reaches: intended for frequent, high-precision surveys of bed, bank, and flood plain morphology, colocated with gauging sites discussed in 4.1.
 - a. A significant number (6 to 10) of reaches from estuary to headwater catchment.
 - b. Study reaches on several tributaries in equivalent lateral points in the drainage width function, but different upstream sediment/nutrient sources and loadings (4 to 6).
 - c. Large wetlands adjacent to Neuse R.
2. Paired basins: similar sized catchments, similarly sited, with fundamentally different predominance of LULC and stream buffers. Size from 0.5 to 40 km² in sites discussed in 4.2.
 - a. Urban-agricultural (2)
 - b. Urbanizing-agricultural (2)
 - c. Agricultural-forested (2)
 - d. Pre-post timber harvesting. (1)
3. Agricultural scale
 - a. Field scale study sites to enable P.I. research, co-located with existing HO instrumentation (ET tower, nearby stream gauging and water quality station).
 - b. Farmer cooperation in terms of documenting application rates of fertilizer, animal waste, crop yields, tillage practice.

c. Purchase rights to use portions of the land for special-use studies.

10.2.7 Specific Instrumentation Needs Unique to Geomorphological Studies

This set of instrumentation needs was developed by considering the unique needs of geomorphological data collection activities in the Neuse River Basin. Many other types of data collection infrastructure are required (e.g. water level sensors, rain gages, water quality samplers, telemetry), but they are common, observatory-wide needs that span the range of observed hydrologic phenomena. Specific scientific infrastructure needs to support the geomorphological aspects of observatory functions include:

1. Brown water navy. We will need research vessels of different size (draft) for access from the Neuse Estuary to perennial low-order streams. These vessels should be:
 - a. DGPS equipped
 - b. Towed sonar
 - c. Coring capability
 - d. Laser side-scanner equipped
2. Surveying equipment
 - a. DGPS
 - b. Total Stations
 - c. Laser scanners (HO network instrument)
3. Instrumentation facilities near intensive study sites:
 - a. Instrumentation storage, calibration.
 - b. Sample preparation.
 - c. Sediment analysis.

11. Social Sciences

Observatories are not “experimental watersheds” where anthropogenic influences on the hydrologic system are few, and those influences that are present are fully documented. Therefore, a challenge will be to provide data to accurately characterize the human activities that affect flows and fluxes. This characterization will require data to document the land and water use choices people make, both as individuals and collectively through governments. The principal contribution of the social sciences to the observatory network is to assist in collecting and interpreting the data that will yield this characterization.

Water and related land use choices of interest range widely. We may have readily available estimates of human influences on the hydrologic regime such as water withdrawals from streams or aquifers, on wastewater pollutant concentrations and flows at wastewater treatment plants. For some data (such as impervious cover) the observatories will have access to aerial images or other sources. However, in other cases there are limited data (or unreliable data) to characterize the effect of human activity on the watersheds. As just four examples, data might be desired on the maintenance practices at storm water retention ponds, on the amount and timing of manure-fertilizer applied to a crop, on outdoors water use in suburban homes or water and chemical application practices on golf courses.

The general approach to fill such data gaps would rely on specific-watershed and observatory-wide household and landowner surveys. The survey process would be a continuing activity of the observatory. However, the survey questions may be modified over time and different survey procedures (mail, telephone interviews and in person interviews) may be employed in different mixes over time. The resulting survey data might be directly used, in combination with other available data, to characterize water and land use in the targeted study watersheds.

Survey respondents in some cases may be reluctant to provide complete data on their practices for privacy reasons or because the effort required in keeping accurate records is

too burdensome. Therefore, the survey design approach may require collecting only partial data on the activity of interest. For example, suppose the interest is in the timing and amount of annual manure-fertilizer application rates to cropland. One set of respondents may be asked for manure application rates in the first three months of the year, a second set for rates in the second three months, and so on. These same respondents would also be asked demographic profile (education, age, etc.) and business questions (full time or part time farming, etc.) These survey responses, combined with other data such as regional location, could be used to develop predictive relationships between the particular water and land use choice (in this example manure-fertilizer application fertilization practices). With knowledge of the demographic characteristics and other factors of the occupants of the study watershed, these statistical relationships could be used to predict watershed specific land and water use choices of interest.

11.1 Key Science Questions

The social science data collection efforts are not governed by particular social science hypotheses. Instead the hypotheses to be tested defined to advance the hydrologic science dictate what social science data are necessary. This said, as a secondary value, such data might prove useful for social science research on people’s water and related land use decisions. Such decisions are made in response to a mix of economic conditions and incentives, cultural and social norms, public programs and constraints and the condition of the surrounding physical environment. Social science research to understand and then predict the water and land use choices people make can improve the design of regulatory and incentive-oriented water resources management programs. The observatory data can contribute to such research.

Data to characterize human activities that may be relevant to any hydrologic science study can be numerous and may be research study specific. However, these activities can be grouped into five broad categories. These categories are described below with an example offered of each.

Category one includes the amount, timing and location of water withdrawals from defined streams and aquifers for residential, commercial, industrial and agricultural uses. For example, a residence located in a study watershed may receive its water supply from a utility outside the study area. In effect, the household “imports” water to the study area.

Category two includes the amount, location and timing of water returned to defined streams and aquifers from residential, commercial, industrial and agricultural uses. Consider again a residential household example. If the household has a private well for its water supply, but is served by a POTW outside the study watershed, then the household “exports” water from the study area.

Category three (related to the second category) includes those activities that can add a chemical constituent to the returned water. For example, water returned to system by a household through a conventional septic tank may include nutrients that find their way into the surface or ground water. In turn the septic tank maintenance choices of the household can affect this nutrient load.

Category four includes land use decisions. The distribution of the land surface in a watershed in impervious cover, in turf grass, in forest, in row crops, in pasture or in animal feedlots all can affect both the pattern and timing of runoff and aquifer recharge and the chemical constituents in the runoff and recharge water.

Category five, related to the land cover choices, are the decisions on how the land in any cover type is managed. For example, residential homeowners in a watershed will use certain lawn chemicals. Other examples include the fertilization practices of farm operators and the community maintenance schedules for storm water facilities in the watershed.

The specific land and water use decision that might be of interest within any of the five categories may be study specific. A describable feature of the survey approach proposed below is that the surveys’ content may be easily varied over time to be responsive to the data needs of particular hydrologic studies.

11.2 Observing Strategy

The Neuse observatory monitors watersheds and ground water areas of different sizes, with different dominant land uses and in different physiographic provinces. Other chapters of this report include a detailed layout of critical science questions, hypotheses to be tested and proposed approaches to testing those hypotheses for these study areas. In these study areas land use changes and land use and water use practices are human activities that must be represented and accounted for if an analysis is to be complete. The social sciences data collection efforts should enhance the ability to characterize the water and land use at each of these different sites.

11.2.1 Data Sources

Categories of land and water use decisions that can affect the hydrologic processes in a study area were described above. Characterization of the water and land use choices in particular places will require the use of widely available data, data collected through the observatory and observatory-partners and data from original surveys. A social science unit (activity) in the Observatory would be responsible for organizing the collection, management and assuring access to these different data bases. However, the essential contribution is the collection of survey data.

11.2.2 Widely Available Data

As will be discussed below, developing for a demographic and business profile of the study watersheds will be essential to making inferences from results of the sample surveys to the study watersheds. The delineated study areas can be initially characterized according to population, population density, and other demographic features using census block data. Additionally agricultural census data, North Carolina Agricultural statistics reports and other sources can be relied upon to characterize agricultural activities commercial activity can be described using readily available federal and state sources.

Because the goal of the social science component is to characterize land and water use decisions in the study watersheds, the social science effort should also include other readily available data that represent human activity.

Agricultural statistics reports and other sources can be relied upon to characterize agricultural activities commercial activity can be described using readily available federal and state sources.

Because the goal of the social science component is to characterize land and water use decisions in the study watersheds, the social science effort should also include other readily available data that represent human activity. A simple example of readily available data would be the location of municipal water supply wells. Another example would be the location of POTWs. Also available should be well pumping records, quality parameters of the delivered water and the service areas of water supply utility. Likewise the service area of the POTW should be readily available as should be the concentrations of pollutants in the discharge and the flow from the plant.

11.2.3 Observatory Data

Some data on human activities will be available through the observatory and observatory-partners. For example, remote imaging and other activities will allow for a mapping of the areas and pattern of forest cover, row crop agriculture, turf grass, roads and other landscape features. As another example, one-time evaluations will identify BMP ponds, drainage systems, riparian buffers, etc. An example of a partner effort is the North Carolina Ecosystem Enhancement Program. This program has initiated a comprehensive watershed planning process (at the 8 digit HUC scale) that over time will inventory and keep an account of these kinds of landscape conditions.

The surrounding physical and biological condition of the watershed affects the choices people make. For example, the pattern, timing and volumes of flows of water in the surface and subsurface affect irrigation and land use decisions. The condition of the biological community in a river can affect choices about where to locate a new housing development. Indicators of physical and biologic conditions will be collected as part of the observatory network and partner agencies and can be used in understanding and predicting water and land use decisions. Therefore these observatory data would be used to predict peoples' water and land use decisions.

11.2.4 Survey Data

Collection Methods: The list of methods below may be used alone or in combination to

collect data on land and water use decisions and the characteristics of the decision makers (individuals, businesses, government agencies).

- Mail surveys are a self-administered instrument where the respondent follows an instruction sheet. Mail survey instruments give the respondent time to gather any information that is necessary for reflection and for gathering records that may be necessary for answering one or more questions.
- Telephone surveys are answered at the time the call is made and rely on respondent recall of past events. Telephone surveys can only collect limited data because they cannot exceed about 5 minutes in length. This method is useful if the desired data is limited in scope and detail. Telephone surveys are useful for collecting demographic data and eliciting opinions.
- In person interviews include the same features as mail surveys, but allow for the interviewer to clarify ambiguities in the mind of the respondent about the questions being asked. This instrument may elicit new data and insights through an open ended question included in the interview process. In person interviews are the most time intensive for the survey team and the respondents, and the most costly to administer.
- Panel data relies on a respondent keeping a diary (analogous to a Neilson television viewing survey) over some period of time. The diary mailed back when completed. Panel data approaches minimize respondent recall problems. Usually panel data approaches provide some level of financial compensation to the respondent and may require securing the respondents consent in advance.

The four survey instruments all might be considered; however the ones that are employed will depend on consideration of their differential costs and whether they are appropriate for the different kinds of data that will be sought. The hypotheses directing any research effort will dictate the data needed and the manner in which such data would best be collected.

Basic Survey Design: Data collected will include: demographic profile data that survey will vary according to the land use of interest. For example, a survey administered to a farm operator may have different profile data requirements than one administered to a suburban homeowner. The use of the profile data helps to assure that the sample survey is as representative of the population being surveyed as possible, where the population is characterized by the widely available data described above. Also, once the survey is administered the profile data can be used to adjust for any biases in the returned samples and to build models that can be used to predict a category of water or land use of interest.

The land and water use data collected through the survey process need not be the same each year. The land and water use data collected through the survey process can be modified to serve the needs of specific research projects supported by the observatory. Initially, certain basic data needs might be identified for observatory study areas, such as residential outdoor water use, residential lawn chemical use practices (amount, kind and season of use), golf course water and chemical use, agricultural applications rates and times of nutrients and manures, BMP maintenance routines by governments and community associations, and the like.

Sampling and Survey Procedures Steps:

The discussion here is for a mail survey, although similar steps are involved in the other survey approaches. The first step is to determine sampling location and frequency, based on the hypotheses being tested and the area of study. As the hypotheses are refined a population to draw the sample from is identified, for example all single family residences. The list of such residences might be obtained from county tax records. At the same time the survey instrument is designed and pre-tested to identify ambiguities and clarify the questions. Once pre-tested the survey is mailed, with appropriate follow-up to maximize the response rate. Data from the returned surveys are recorded in a useable and accessible data management format.

11.2.5 Using the Data: A Simple Example

A PI needs to know the application of water to lawns, golf courses and public areas (turf

irrigation) in a large study area and the source of that water. *Widely available* data (ex. census or tax records) might be used to identify how many single family dwellings (assuming they have some lawn area) there are in the area (the size of the population to be sampled). The same source might be used to characterize some important aspect of the dwellings, such size of the dwelling unit and household income of the owners or renters. In this case the distribution of dwelling unit sizes in the population would be calculated, as could the distribution of income among the households. *Widely available data* might also be used to determine how water is supplied to an area, as between public water systems and private household wells. For public water systems widely available data might report the proportions from local surface sources, ground water pumped inside the area and water from outside the drainage area. *Widely available data* might also identify the location and size of area golf courses and public recreational fields. Observatory or observatory-partners data might also be a source for such data.

Suppose there are going to 300 surveys (for example, mail surveys) of single family dwellings and there are 5000 such dwellings in the area. (A similar discussion could be developed for golf courses, etc.) The *survey data* collected from the 300 surveys will be used to draw inferences about the 5000 residential dwellings. The data described above can be used to set up the sampling strategy to determine a sampling strategy that will secure a representative response. To test how representative the response actually is, the survey would include profile questions that parallel the data that is available for the population as a whole. In this example it would be possible to determine whether the surveys respondents were representative of the population in terms of dwelling size, household income and whether the water source was by private well or from a public system.

Survey data, in combination with *observatory data* and *widely available data* might be used to develop a predictive relationship that allow for making inferences about water and land use choices from results of the sample surveys to the study watersheds.

12. Remote Sensing

Remote sensing activity as part of the HO will be used for:

- support of science questions and hypotheses posed in previous chapters,
- development and testing of remote sensing data, algorithm performance and reliability in estimation of critical surface and atmospheric state and flux variables,
- data assimilation for continuous and event based models of watershed behavior
- central components in the development of scaling framework to extend intensive measurements at the catchment level to the full Neuse Watershed (NW).

Radar estimation of precipitation fields is a form of remote sensing that was extensively treated in chapter 5, and is not further treated here. The Hydrologic Observatories will provide unparalleled infrastructure to develop and test remote sensing estimates of hydrologic science storage and flux quantities. As such, they are expected to be used extensively in association with EOS satellite products (e.g. from MODIS TERRA/AQUA, ASTER), as well as new and developing sensor systems (e.g. HYDROS), by providing nested sampling of surface conditions over significant land areas and environmental gradients. Orbital and airborne remote sensing will be extensively used in the Neuse Watershed Hydrologic Observator (NW-HO) to develop multi-resolution estimates of state and flux variables as part of scaling strategies to the full watershed. We will make use of remote sensing products from all forms of orbital, airborne fixed wing and helicopter based sensors. The latter sensors will be deployed periodically as single instruments or in tandem as part of intensive field campaigns (IFC). The major hydrologic variables we will characterize with remotely sensed products include soil moisture, surface energy budget terms, land cover, canopy cover, leaf area index and phenology, flood inundation extent, water quality as well as high resolution topographic and land use/land cover patterns and change. We will make use of combinations of

optical, infrared, thermal and microwave systems, including active and passive.

Research with high resolution imagery concentrated on densely instrumented sub-catchments will be complemented by progressively lower resolution image products extending to the full watershed. This remote sensing scaling strategy will make use of both the regularly scheduled, long term field sampling designs discussed in earlier chapters, and IFC to collect sufficient ground measurements at the time of image acquisition. These latter activities will build on the community's experience in a set of remote sensing-field IFC, with the major advantage of the long term, large scale context of monitoring and sampling the IFC will be embedded within.

In addition to the dense sampling of the IFC to establish remote sensing estimates of surface spatial patterns of key variables, the combination of long term hierarchical sampling coupled with the set of continuous simulation models that will be operated and frequent satellite remote sensing information will form the basis of a data assimilation framework. Specific evaluation of the benefits and improvement in model performance and forecasting skill for estimating space/time patterns of targeted hydrologic processes gained by specific assimilation methods and remote sensing image information will be carried out. Model development and testing activity is described further in Ch. 13.

Existing high resolution data resources: As discussed above, extensive high resolution remote sensing coverage (ETM/SPOT) of the full watershed is available and held by a variety of federal and state agencies with leaf on and leaf off imagery from 1999-2000, and additional TM coverage at 2-3 year intervals beginning in 1985. AVIRIS coverage of the Neuse estuary and mainstream have been collected within the last five years at 4m and 20m resolution (<http://aviris.jpl.nasa.gov>). Digital color orthophotography acquired in 1998 is available for the full state, as is a high resolution LIDAR data set acquired by a partnership of the state with NASA and FEMA in response to the devastating 1999

Hurricane Floyd flooding. The recent ETM/ SPOT image base has been used in conjunction with the digital orthophotography to develop a hierarchical land use/land cover data set (Lunetta et al 2002), with an extensive network of training and validation field plots (EPA web site) including ~1500 geolocated plots, of which ~400 are targeted to riparian sites. Additional coverage, including Landsat MSS dating to the mid-1970s, and a set of airborne optical-NIR, microwave and experimental lidar products (e.g. VCL) exist for limited areas in and around the NW. Hyperspectral imagery from light aircraft (estuary and lower river) have been periodically collected in conjunction with water quality sampling by the Atlantic Coast Environmental Indicators Consortium (<http://www.aceinc.org/>).

12.1 Key Science Questions

The following remote sensing science questions are posed as extensions of investigations discussed in previous chapters:

- a. *How can we combine frequent, low resolution imaging of vegetation cover with high resolution, infrequent imaging to infer spatial and temporal detail of surface phenology and canopy cover outlined in Ch.3 and 6.*
Needed: MODIS composite period phenology along with multiple high resolution optical/ NIR imagery (e.g. ETM+, ASTER) during green-up and leaf-fall periods with weekly estimates of life form specific phenology.
- b. *Under what conditions can remote sensing optical and thermal information be used to estimate land surface evaporation or evaporative resistance (measured in Ch.6) and what are the effects of sensor resolution?*
Needed: Simultaneous collection of remotely sensed thermal emission, optical and near infrared reflectance at multiple resolutions (e.g. MODIS, ASTER), along with surface tower flux measurement of evaporative and energy budget components in a range of catchment conditions.
- c. *How well can active and passive microwave imagery characterize surface soil moisture under different topographic and vegetation cover conditions, as measured in Ch.6? Do high resolution estimates of surface soil moisture from*

active systems aggregate to form soil moisture estimates comparable to lower resolution passive microwave system estimates?

Needed: Soil moisture measurement network in a set of diverse catchments, along with airborne and orbital microwave sensors. High resolution measurements of surface topography, canopy characteristics and surface roughness elements.

- d. *What key water quality parameters measured in-stream by techniques discussed in Chapters 9 and 10 can be reliably estimated by hyperspectral remote sensing systems?*

Needed: Airborne high resolution remote sensing systems deployed along estuary-mainstream-major tributary transects in associated with field sampling of water quality parameters.

12.2 Observing Strategy

The NW-HO will not maintain its own aircraft. Airborne imagery will be acquired by

1. Leasing flight time from commercial sources, either with available sensors from these firms or with special or prototype sensors mounted in the commercial platforms.
2. Scheduling and coordination of image acquisition from NASA airborne sensor systems (e.g. SAR, AVIRIS), through existing NSF consortia (e.g. NCALM) and with other agencies.

It is expected that much of the orbital and airborne remote sensing activity will be conducted as part of HO network level activity. Important economies of scale will need to be coordinated at this level, specifically with commercial sources, but including network wide image information with NASA and other agencies. This will require significant coordination with the HO network, the HMTF and the HIS. New sensor development for specific applications will be conceptualized as part of NCHS activity, and developed and deployed in association with the HMTF.

The following information will be estimated using combinations of airborne and orbital remote sensing systems in association with field sampling outlined in previous chapters:

- **Phenology of canopy cover:** Vegetation phenology of canopy cover and leaf area index will be gained from MODIS (standard product) for composite periods and from high resolution imagery (e.g. ASTER, ETM, AO1) four to five times (depending on cloud cover) through the growing season and two to three times in the non-growing season. This will make use of the network of canopy sites for field measurement of LAI which will be chosen from the set of tower sites (Ch.6) and additional stands as necessary to capture the range of vegetation communities in the NW. LAI and canopy cover will be estimated with a set of instruments including LICOR LAI-2000, hemispherical photography and TRAC devices (latter to gain gap frequency distributions). We will investigate multiple approaches to estimating measured LAI from high resolution imagery using simple regression to complex radiative transfer based models.
- **Evapotranspiration/resistance:** Growing season evaporative resistance/evaporative fraction estimates will be estimated from MODIS (TERRA and AQUA) for composite periods and on days with cloud cover below a specific threshold during the growing season, and from high resolution imagery (e.g. ASTER) four to five times a year. Tower flux (Ch.6) as well as small catchment water balance will be used to provide estimates of evapotranspiration from sub-daily to multiples of MODIS composite periods. We will test whether high resolution estimates of evapotranspiration and resistance terms can be aggregated to yield lumped estimates as developed from MODIS. Remotely sensed patterns of ET/resistance at the stand level will also be used for comparison with distributed ecohydrologic models (e.g. DHSVM, RHESSys, TOPLATS).
- **Soil moisture:** Active and passive polarimetric microwave estimation of backscatter will be collected. Airborne and orbital active microwave acquisition will be coordinated in intensive field campaigns, during which canopy and surface roughness conditions in a subset of the TDR network sites will be sampled. The permanent TDR network (Ch.6,7) will be augmented during these field campaigns with more spatially extensive synoptic sampling using portable TDR. We will concentrate intensive field campaigns to attempt to capture wet and dry periods and the transition periods in between as a test of the concepts of dominant soil moisture states discussed by Western and Grayson (1998).
- **River water quality:** High resolution airborne hyperspectral imagery of the Neuse and major tributary mainstems and estuary will be collected seasonally and following major storm events to estimate fine sediment load and key water quality parameters. Overflights will be coordinated with synoptic water quality sampling from the set of instrumented stream gauges (ch.4) as well as ship based sampling (ch.10).
- **Channel and floodplain modification by extreme events:** High resolution airborne LIDAR elevation data will be collected along mainstream and tributary reaches on an annual basis, and following extreme events (e.g. hurricane) with repeat data collection following major events with log-stepped time intervals (Ch.10). This will be coordinated with field resurvey of benchmark cross sections to test long term trends in channel reach geomorphology as well as transient response to major events.

13. Modeling

Models are essential for several of the important tasks conducted at an HO. For example, design of optimal monitoring programs in space and time requires a model of spatial/temporal variability. Likewise, interpolation of limited observations and extrapolation to larger scales requires a similar model that should improve as observations and science increase our understanding of spatial/temporal patterns. Estimation of basic properties such as residence time at various spatial scales requires a conceptual model of fluxes, flowpaths, and stores, along with a mathematical model that can be used to estimate the property of interest from the observations. Improvements in predictive understanding will be assessed using periodic benchmarking; this will require process models that can be used to address the science questions at various scales.

To serve these purposes of design, estimation, and prediction, models should have estimable error terms. A number of the extant physically-based and conceptual water models simulating watershed and waterbody processes have over-parameterization problems and have not yet been subjected to a thorough uncertainty analysis. Simpler statistical models will generally support these key tasks, but they may not characterize the detailed response of interest.

Therefore within the HO (in conjunction with the HIS and Synthesis Center), efforts should be undertaken to develop models and to apply modeling techniques that facilitate uncertainty analysis. For example, techniques such as regionalized sensitivity analysis (RSA; Hornberger and Spear 1981), generalized likelihood uncertainty estimation (GLUE; Beven 2001), and Markov chain Monte Carlo (MCMC; Gilks et al. 1996) allow estimation of parameter distributions for over-parameterized models. These techniques effectively acknowledge the equifinality thesis of Beven – that many models, or many different parameters sets for a given model, will fit available data equally well.

The notion that we can “get the processes right” for hydrology or water quality prediction in a catchment with a single physically-based model and a unique set of parameters is not

realistic given space/time variability and limited measurement systems. A more reasonable expectation involves the use of conceptual models that provide an approximate mathematical characterization of important processes, combined with effective parameter estimates. Data assimilation and Bayesian techniques also offer promise for integrating observations with model forecasts and for combining information. Application of one of the above-mentioned techniques might then provide the basis for hypothesis testing, prediction, and benchmarking.

The HO will provide opportunities for extensive model development, model comparisons, and model evaluation efforts. Density, quality, and redundancy of data will allow comprehensive model sensitivity and error propagation studies. The establishment of benchmark datasets and the augmentation of model predictions with error terms will allow the community to monitor and document progress of scientific discovery and assess the consequent practical benefits. The HO also will serve as a test ground for instrument intercomparison experiments stimulating technological developments in observational capabilities of the hydrologic community.

Such studies (e.g., model development, instrument intercomparison) will be a key function for the HO staff, but may also be of concern for other scientists attracted to work at the HO. As the HO staff is the most familiar with the area and the details of instrument deployment and the peculiarities of the systems that may have escaped the initial observational network design, they will provide insight into any modeling studies. We anticipate that model intercomparison studies will exploit the existence of the CUAHSI HIS and Synthesis Center activities.

13.1 Key Science Questions

In Section 12.2 and elsewhere in this document, the distinction is made between the “core data” supported through the base grant of each HO and the separately funded science of a particular HO. In keeping with this distinction, the hypotheses below are identified as “core,” “science,” or “both.”

- a. Model-based monitoring design for the hydrologic system can be used to identify gaps in data. **(core)**
Needed. A model that quantifies the uncertainty in spatial/temporal patterns and can be used to estimate the value of new information (e.g., additional observations).
- b. Model-based inference through interpolation and extrapolation of limited observations can be used to provide reliable continuous estimates of key hydrologic variables. **(core)**
Needed. Overly-dense observations networks that provide “set-aside” data for comparisons with interpolations and extrapolations based on a subset of the observations.
- c. Models integrated (using Bayesian analysis or data assimilation) with observations can provide meaningful predictions of the state of the hydrologic system of interest. **(core)**
Needed. A redundant observational system where some data can be withheld to independently evaluate model predictions.
- d. Identifiability problems in models associated with too many parameters and too few observations can be addressed with Bayesian methods or other approaches (e.g., GLUE, RSA) that yield multi-dimensional distributions/regions for parameter sets. **(both)**
Needed. Redundant observations that allow investigations with quantified comprehensive description of uncertainty. The HOs provide an opportunity to investigate this issue for a plethora of hydrologic models.
- e. Model ensemble predictions outperform (based on approved model performance criteria) single model predictions.
Needed. Long term observations so that ensemble based prediction can be evaluated in a probabilistic sense. The degree to which the hypothesis is true may depend on the hydrologic variable, type of the model, and the performance criteria.
- f. Poor performance of model ensembles identifies gaps in our understanding of the modeled process. **(science)**
Needed. Specialized field experiments, new observations, creative data analyses. New approaches including new models should be

tested and evaluated against well established benchmarks. The HydroView infrastructure of CUAHSI will provide systematic and organized efforts for the development of benchmark data sets and models.

13.2 Modeling Strategy

There have been relatively few organized efforts in the hydrologic community to evaluate modeling progress and to identify major gaps in understanding. For example, there has been a plethora of rainfall-runoff models but very few rigorous comparisons of these models. Exceptions include World Meteorological Organization’s (WMO) standardization of methods and equipment, but these rarely include cutting edge science and technology. While the atmospheric sciences research community organized efforts to develop a community modeling system, in the hydrologic community discussions on such topics are essentially absent.

The HO basic grant can support for certain “core data” modeling tasks: (1) model based monitoring design and inference, and (2) a community hydrologic modeling system for descriptive and predictive understanding. The first concept results from the fact that even the best instrumented basin falls short in terms of the observational network density in view of the tremendous range of variability displayed by many hydrologic variables and the basin properties that control hydrologic processes. Thus, model based interpolation between the observations is the only viable means to provide continuous space and time coverage to guide monitoring design and for subsequent scientific inference from limited observations.

The second concept will speed up advancement of the hydrologic science and the efficiency of hydrologic prediction. A modular design of a hydrologic modeling system will allow coupling of the different components of the hydrologic cycle and models of water quality and quantity. Such a system will facilitate integration of new observational technologies, new developments in informational technologies, evaluation of new methods for model parameter estimation, and testing of new theories.

Important complementary activities that qualify as separately funded science studies include model intercomparisons; ensemble prediction; data assimilation, Bayesian inference, and other

methods for combining information; and uncertainty assessment. Model intercomparisons and development of benchmark data sets to assess model results are important for the systematic monitoring of the progress made by the hydrologic research community. Data assimilation and error analysis are essential elements of this process. Clearly, an important performance measure of progress is the reduction of the predictive uncertainty. The HOs provide observational infrastructure which, when combined with other elements of the HydroView, will ensure steady progress and advancement of the hydrologic science.

13.3 References

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- Gilks, W.R., Richardson, S., and Spiegelhalter, D.J. (eds). 1996. *Markov Chain Monte Carlo in Practice*. Chapman and Hall, New York.
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14. Data Communications

Remote data transmission is essential within an HO to minimize labor costs and allow near real-time detection of equipment failures. Recent advances in telemetry, such as cellular modems and low-power broadband transmissions offer significant improvements over older technologies. However, power demands associated with current technologies place limitations on the practical use of telemetry. Contemporary data loggers consume very little power and can operate for months on battery power. A transmitter/receiver requires an order of magnitude more power. There are two operational modes to consider:

Mode A) Battery Power Only: If the equipment is battery operated, the telemetry (transmitter/receiver) cannot operate continuously. The way to operate in this situation is to have the data logger collect data as it normally does, and turn on the transmitter at set intervals, send the data, perhaps wait a short while for instructions, and then go to sleep. If operating in this mode, www-accessibility is not particularly useful. Solar panels come to mind as a potential solution. However, calculations show that solar power really only partially alleviates the problem. You can operate longer or transmit more frequently, but the transmitter still can't be always on.

Mode B) Line Power: Given access to 110V power the data acquisition hardware/ datalogger can be connected to an embedded PC and radio and effectively "publish" you equipment on the internet. There are many sites that show how to make a weather station where the data is displayed in real-time on some website. Often, where you have 110V power, you probably have or can get a phone line, so a radio is not needed. Another approach is to use the 2.4GHz technology (basically internet router technology). John Helly has done some great work in this regard. See: <http://hpwren.ucsd.edu/news/040629.html>.

In mode A operation, there are many radios (see for example www.maxstream.net), but the best option is probably cellular modems. For examples, see www.feeneywireless.com/products/modems/enfora_Spider_MT.shtml. Another company is DataRemote (www.dataremote.com). These are remarkable devices. They have an

RS232 port that you can connect to a data logger. By issuing the appropriate "AT" command, the modem dials the phone company (e.g. Verizon or Sprint). Once connected, the cellular company becomes the ISP and the modem has an IP address that you can ping, etc. Anything that the logger writes to the RS232 port becomes IP packets that you send to the modem becomes serial data. Thus, the modem can use telnet to communicate with a computer, or use an http connection, or some other protocol. For an extra fee, the telephone company will provide a static IP address if random access to the device from a central location is important. To make the system work requires some programming. For a proposal it is sufficient that reviewers understand it can be done. The modems cost about \$350 (but prices vary). They have very sophisticated power management; operate over extended temperature ranges, etc. Phone companies charge about \$10 per month for 2 MB of data. In some rural areas coverage may be a problem.

In mode B operation, you could have the same radios, but they would be always on. With the cellular modem it is important to realize that if you get the phone company's data plan (as opposed to voice plan) then you only pay for bytes transmitted, and you can dial in, get an IP and stay on indefinitely without incurring any costs.

Dr. Anton Kruger, and Electrical Engineer at the University of Iowa is designing a cell-modem based datalogger for interfacing with raingage networks. These devices can also interface with soil moisture probes and other hydrometeorological sensors. It is anticipated that this cellular modem will operate unattended for 2 months from a deep-cycle 12 V marine battery, transmitting data twice a day to a cellular ISP. When it is triggered the device can send data more frequently (e.g. when raining the device will send data every 5 minutes). The estimated unit cost (including cell modem) will be about \$6,000 each. Based on quantity purchasing and anticipated design improvements, they are estimated at a cost of \$4,500 each in the budget below.

The table below shows estimated costs for a wireless "backbone" for transmission of data.

This estimate includes leasing 6 T1 (1.5Mb/s) data lines to service the 4 polarimetric radars, and two remote data collection centers. This budget also includes 20 additional mode A cellular modems for transmission of soil moisture and other data sources from sites not adjacent to a stream gage, flux tower, or rain gage, and 20 A.C. powered cellular modems for sites with wall power.

Note: data telemetry costs are already included in the stream gaging budget (54 sites). The rain gage network includes mode A cell modems (100 sites). The cost of the cellular modem is included in the flux tower budget, but not data communications. Communications costs in terms of annual expenditures are included below for the entire network, and are equal to approximately \$103,000 per year.

Table A.14 Data Communications Budget

CLASS	QTY	DESC.	UNIT PRICE	EXT. PRICE
DATA/COMM	20	Battery operated cellular modem (Mode A)	\$4,500.00	\$90,000.00
EQUIP.	20	A.C. powered cellular modem (Mode B)	\$350.00	\$7,000.00
		TOTAL CAPITAL COST		<u>\$97,000.00</u>
 ANNUAL COSTS				
	54	DSL Wireless access (assumes DSL \$35.00/month)	\$420.00	\$22,680.00
	120	Cellular modem access points/accounts (\$18.00/month)	\$216.00	\$25,920.00
	6	T1 line lease, \$750/mon each.	\$9,000.00	\$54,000.00
		TOTAL ANNUAL OPERATING COST		<u>\$102,600.00</u>

15. Operation and Implementation of Hydrologic Observatories

Previous chapters have discussed the definition of core data and how it is distinguished from investigator data. In addition to the equipment and staff at the HO, the core data is a vital part of the “infrastructure” of the HO. It can be seen as a “community product,” critical to advancing hydrologic science, yet requiring too great of an investment of time and effort to be feasibly undertaken by individual investigators. The HO—its physical infrastructure, its professional staff, and its core data—must serve as a resource to the entire hydrologic sciences community. An HO is not simply a large research project operated by the Observatory Design Team (ODT), who designs the core data. Indeed, one important metric of success for HOs is the number of researchers, outside of the ODT, that they attract. An additional set of metrics will include how the site is used for education and to help in water management and policy formation. Although it is premature to provide a precise threshold of participants to define “success,” an HO where only the ODT is working is clearly a failure. In this chapter, the operation of hydrologic observatories is considered, with particular attention paid to the roles of the (ODT), the observatory professional staff (OPS), and CUAHSI.

15.1 Role of the ODT

15.1.1 Designing Core Data

The ODT’s primary function is to design a data collection and interpretation strategy that estimates the three fundamental hydrologic characteristics of the basin: the flux, flowpath and residence time of water, sediment, nutrients, and contaminants among the atmospheric, surface and subsurface stores of the basin. The ODT develops the conceptual framework for the basin by defining these “stores” —their number and their spatial (and, potentially, temporal) extent. These stores are the conceptual “boxes” into which the basin is divided.

The central finding of this report is that a prescriptive approach, either directly defining data series to be the core data or defining a set of hypotheses that all HOs would be designed around, is infeasible for a network operated by independent academic scientists. There is not,

nor should there be, a central management team that would be necessary to make these decisions. Rather, independent teams of scientists, while pursuing their own research, are to specify how to determine these fundamental characteristics can be estimated either by direct measurement, remote sensing, or modeling inference. This approach also realizes the tremendous diversity of environmental conditions found in the United States. No single management team can determine all the details of core data—what to measure, where to measure, how frequently to measure and what techniques to use—for arctic tundra, prairie pot holes, glaciated upland, desert and highly weathered piedmont terrains. Scientists with intimate knowledge of the field site, and the intuition that comes from that knowledge, are needed to design a meaningful characterization of the landscape. Note that this does not mean that there would be no coordination of the type of information required to be collected in each site, just that the specific control volumes and methods of measurement and estimation will vary by necessity between different environments. In addition, methods of gaining common information needs may be coordinated and rationalized between HO by CUAHSI as the network evolves and as discussed below.

We anticipate that the cost/benefit ratio for some data series will be so beneficial that their collection is obvious. Such data might include high-resolution digital elevation models, surface-water gaging networks, and rain-gage networks. The cost/benefit ratio increases as more sites are added to these networks or additional LIDAR surveys are performed because the marginal value of each additional gage or survey likely decreases, mostly because it serves a smaller community of scientists. Also, as one considers more expensive data—whether water chemistry, biological sampling, or high-resolution radar precipitation networks—the cost/benefit ratio also increases due to higher unit costs. These subtleties lie at the heart of defining effective HO. Should resources be directed to operating an additional stream gage, an additional observation well, or isotopic analyses? The answer, of course, depends upon the question. That is the primary reason why the design of HOs must be hypothesis-driven.

If our contention that these characteristics are needed for most hypotheses is true, estimating these fundamental characteristics will be intrinsic to the research and, therefore, consistent with the scientific goals of the ODT. However, the core data and the context for interpreting them to estimate the fundamental characteristics are to be made immediately available to the community. The ODT has invested much effort in designing the core data, but does not have any prerogative for first publication of the data or analyses of it.

What, then, are the incentives for a team of scientists to design an observatory? We see the following:

- The core data and the basin conceptualization are designed precisely to fit the ODT's research interests. The ODT can write proposals to other competitions to pursue these interests.
- The ODT has "first-publication" rights to a subset of data that they specify. These data will eventually be released in the same manner as the core data after a specified period, similar to data policies that exist for LTER sites. For the pilot phase of HOs, a single proposal will be written to perform both research and the community service aspects of the work. This approach, called an "integral science model," is in contrast to other large-scale community efforts where an infrastructure proposal is considered separately from research proposals. There is no predetermined allocation of resources between these activities. Teams are free to propose any allocation, but those proposals which have a larger proportion of resources going to the community product will be favored over those which don't. Therefore, the proportion of resource needed to reward scientists for doing this work will be determined by competition. Once HOs become operational and greater experience has been gained in the design and operation of HOs, the infrastructure component will be competed separately from the science component.
- The HO is operated in the basin that the ODT is most interested in.

15.1.2 Development of Annual Workplan

Once the core data is defined in the design process, the ODT must develop an annual workplan that lists all data to be collected and must specify location, timing, frequency, protocols for data

and/or sample collection. The annual workplan is, in effect, the contract with the community about what core data will be provided by the HO.

This formal specification of the core data serves two important roles. First, it can be reviewed by CUAHSI to assure comparability and completeness of core data across HOs. (See next section.) Second, it can be passed to the Observatory Professional Staff (OPS) for execution and eventual population of the HydroViewer, the common data platform provided by the CUAHSI Hydrologic Informatics System. This second step is critical to assure that the ODT does not control the core data nor limit its distribution.

Successful execution of the annual workplan by the OPS will require frequent communication with the ODT as unexpected environmental conditions arise, as equipment malfunctions, and all the other things endemic to field work go wrong. The ODT serves as consultants to the OPS and makes judgments on how to proceed when the original plan cannot be executed as planned. However, the ODT is not involved in day-to-day field operations. This allows the ODT to focus on their research so they are not unduly burdened with the details of running a large field operation.

15.1.3 Review of Annual Workplan

The annual workplan contains the ODT's approach to characterizing the HO across scale, including the data to be collected, conceptual models of the HO, and interpretive approaches to estimating these fundamental characteristics. Although the ODT determines the latter two elements of the workplan completely, the data to be collected are subject to review by the Standing Committee on Hydrologic Observatories, CUAHSI's governing committee for HO's. This committee seeks to assure data comparability across HOs and will negotiate any concerns about comparability with the ODT. Furthermore, if there are data gaps in the proposed core data at one HO when compared to others, the ODT and the committee will discuss how to close these gaps.

The guiding principle behind these negotiations is to maximize the scientific output of the HO subject to the constraint of data comparability. Resource constraints may force that certain scientific objectives of the ODT

be sacrificed to achieve data comparability or completeness. The core data must be adequate to advance on some scientific fronts, even if everything that is wished for cannot be done. These guidelines will have to be adapted as more experience is gained. We foresee that workplans for the initial few HOs will not be strongly constrained by network considerations, but as later HOs come on line, more specific expectations of the core data content will have developed. Future solicitations for HOs can contain these expectations to minimize the difficulties of these negotiations.

15.2 Role of Observatory Professional Staff

The Observatory Professional Staff (OPS), headed by a PhD-level Site Director, has four responsibilities:

1. Collection and quality assurance of Core Data, as specified in the annual workplan,
2. Population of HydroViewer data system with the core data
3. HO site administration, including scheduling and siting of research teams, as well as securing and administering access permits to wilderness areas, private lands and other restricted-use lands
4. Support of research teams through maintenance of experiments, field collections, etc.

The first three of these responsibilities are primary; the fourth is to be achieved as resources permit.

The existence of the OPS distinguishes HOs from other research sites, such as LTERs. OPS most closely resemble the professional USFS or ARS research staff, present at many LTER and ARS sites, but, unlike the USFS researchers, the OPS exists to serve the needs of the research community. Their existence permits a separation of the community-service function of the HO (collection and publication of core data, site access) from the science interests of the ODT. Thus, the ODT is just one group of researchers at the HO, but does not control the HO core data or access to the site.

The proper composition and size of the OPS is subject to many factors, but, at the default funding level of \$3M/year in operating

expenses, we envision a staff of 14 FTEs. Beyond the Site Director, between 1 and 2 FTEs will be required for data quality assurance and data base maintenance, 3 to 5 FTEs for junior technicians for field data collection, 2 to 3 FTE's for senior technicians, and 1 to 3 FTE's for laboratory personnel, depending upon how chemical and isotopic analyses will be accomplished at the HO. The variables to be considered in determining the staff include the geographic extent of the instrumentation, the complexity of the instrumentation, site access difficulty, and the environmental harshness of the HO.

From past field experience, we offer the following guidelines for consideration of OPS composition:

- Some long-term professional staff is critical for continuity of HO operation. Graduate and undergraduate students can be an important supplemental labor pool, but cannot be relied on exclusively to operate an HO.
- Up-front capital investment for automation of sample collection and analysis, as well as hardening of field instrumentation to withstand environmental extremes and tampering is usually a wise investment and improves the reliability of data collection.
- Whatever can go wrong, will go wrong. Therefore, the ability to remotely acquire data to diagnose equipment from the office is critical to efficient site operation. Wireless and satellite communications make such access feasible; it is a critical investment.
- Timely population of HydroViewer with core data is a critical measure of success for the HO. Sufficient resources must be allocated to allow for timely data quality assurance, posting to the database, and database maintenance.

The Site Director will be critical to the success of an HO. This person must be familiar with research and field work, but cannot be on a standard research-oriented tenure track. Although the administrative and technical duties may not be full time, they will likely be at least 75% of the position. Part-time research is to be encouraged for this position so that the Site Director has a stake in the science and remains current in his or

her field. Creative and flexible arrangements will be needed to attract the best candidates for this position, but unrealistic expectations of research time must be avoided.

Senior federal research scientists are a good example for the Site Director. These scientists often have a majority of their time assigned to administering scientific resources, but retain a portion of their time for research. The Site Director should have a substantial research track record and have stature in the hydrologic sciences community.

15.3 Role of CUAHSI

CUAHSI represents the community interest in the operation of the HO and will take an active role in marketing the HOs to the environmental science community. CUAHSI's Standing Committee on Hydrologic Observatories will review annual workplans of each HO and assess the performance of the OPS. The SCHO is the forum where the "network" aspects of HOs will be debated: what protocols are acceptable? Does the core data provide a sufficient characterization of the HO? How should core data collection be prioritized? Is the HO staff adequately performing its duties in light of the vagaries of weather, equipment failures etc. to deliver the core data? This will require effective interaction between the site manager and SCHO.

These details are numerous and can appear to be overwhelming. This complexity is one reason for starting with a pilot operation of a few HOs until experience can be gained. Much of the groundwork for operating networks of environmental observatories has been laid by the Federal science community. Standardized data dictionaries, meta-data standards, and database requirements have been developed over the past few decades by groups such as the Intergovernmental Task Force on Water Quality Monitoring (now the National Water Quality Monitoring Council) and the Federal Geospatial Data Committee. Although the recommendations of each of these groups are not complete in themselves, they provide an important starting point for SCHO deliberations. There is no question of the importance of setting such standards for effective operation of the network. The challenge is to do it in such a way to balance flexibility for

the individual scientist with documentation and standardization of the data. The core data will be subject to more rigorous comparability standards than investigator data, which will likely have only documentation requirements for entry into the common data platform.

The other important role for CUASHI is "marketing" HOs to environmental scientists so that they are aware of the services and data provided by the HO. A critical piece of that marketing strategy is HydroViewer, the common data platform that will provide web-based access to core data. This is probably not sufficient to attract scientists to work at HOs. Funds will be requested for small travel grants to permit scientists who are serious about working at an HO to visit the site; in addition, CUAHSI workshops and meetings will be scheduled near to the HOs to increase exposure.

15.4 HO Management

The primary concept shaping HO management is to allow the ODT to remain as one scientific team using the HO, but not managing the HO. This is both to take a large burden from academic scientists whose interests do not lie in site management and to assure equal access to the site (and its core data) for all members of the community.

Ultimately, OPS may be direct employees of CUAHSI reporting to the Site Director who, in turn, reports to the CUAHSI Executive Director. For the pilot stage of HOs, however, OPS will likely be employees of a university on a subaward from CUAHSI. These staff, with the possible exception of the Site Director, should not be research-track employees, but, rather, technical and professional employees. Some universities can easily accommodate such positions; for others, special arrangements may need to be made.

This arrangement significantly differs from other large NSF awards, such as Science and Technology Centers, where the Director is the PI overseeing both science activities and center administration. Removing the ODT from overseeing the site could compromise the core data if the OPS does not have a sufficient scientific stake in the data to ensure its quality and completeness. Furthermore, the ODT must be involved in making mid-course corrections if the

annual workplan can no longer be accomplished for any reason, such as weather anomalies, equipment malfunction, or unanticipated delays in installation.

The Neuse team believes that the proposed independent Site Director model (where the Site Director reports to CUAHHSI and not to the PI of the ODT) is the preferable model to ensure community access. Lines of communication must be kept open with the ODT, but that can be readily accomplished, particularly if the Site Director is located on the same campus as the PIs of the ODT. The PI of the ODT should request substantial salary for the first years of the HO, perhaps as much as half time, during the design and initial years of operation. This amount of salary support will be necessary to get the HO up and running but could be reduced to summer salary once the HO is operational.

15.5 Implementation of Hydrologic Observatories

15.5.1 Developing a Network of Hydrologic Observatories

Given the complexity of operations for HOs and the inexperience of the academic community in operating such field facilities, the team recommends the establishment of a pilot network of approximately 5 locations. Site selection should be staggered to permit experience to be gained in site operation. However, we suggest that two HOs be selected in the initial competition to allow for consideration of network aspects from the beginning of HO operation. The SCHO from the outset must consider how HOs are to be networked together. We anticipate that network constraints will be minimal for the first two HOs, but will steadily grow as more HOs are brought on line.

We recognize the danger in the approach that we have advocated for each HO to operate so independently from one another that no network is achieved. We anticipate that as ODTs develop core data, significant commonalities will emerge. There will be “non-controversial” core data where the cost/benefit ratio is so beneficial that its collection is obvious. The scope of this data will emerge as more stations are added to the pilot network.

15.5.2 Schedule for Implementation

The following timeline assumes that an NSF program announcement for the initial competition for HO's will be released in January, 2005. If that proves to be infeasible, the schedule can be altered accordingly. Elapsed time from the release of the program announcement is indicated parenthetically.

January, 2005 (+0 months). NSF Program announcement of HO competition released.

April, 2005 (+3 months). Proposals due to NSF. Review process begins.

October, 2005 (+10 months). Initial 2 HOs announced. CUAHHSI will award each team \$250,000 from existing funds for the development of the annual workplan. NSF award will be contingent upon receipt of acceptable annual workplan. The precise amount of time to complete the workplan is not known, but this is a substantial effort.

April, 2006 (+1 yr 3 mo). Draft annual workplans due to CUAHHSI SCHO. Target date for “complete” data collection is October, 2006. Initial assessment of plan, highlighting construction and staffing requirements.

May, 2006 (+1 yr 4 mo). Recommendations of SCHO returned to ODTs and NSF. Initial award of NSF funds for construction, staff hiring and agreed-upon data collection.

August, 2006 (+1yr 7 mo) Final annual workplan due to CUAHHSI SCHO.

September, 2006 (+1 yr 8 mo). Approval of workplan. Finalization of NSF budget.

October, 2006 (+1 yr 9 mo). Target date for HO “opening” with HydroViewer populated and operational with non-HO collected data and core data collection begun.

December, 2006 (+1 yr 11 mo). Townhall/Poster session at Fall AGU highlighting initial 2 HOs, core data, and facilities for researchers.

Jan-Apr, 2007 (+2 yr 0-3 mo). CUAHHSI conference(s) at each HO to educate community about site.

May, 2007 (+2 yr 4 mo). Second annual workplan due to CUAHSI SCHO (and all subsequent years).

June, 2007 (+2 yr 5 mo). First NSF Hydrologic Science panel to receive proposals for research at HOs.

January, 2008 (+3 yr). Program Announcement for Third HOs, with the final two announcements the following Januaries, followed by competition and award..

This schedule could be continued, but becomes more speculative in the out-years. However, one important date should be mentioned. The initial 2 HOs will have 3 years of operational experience by October, 2009. During the following year, a more extensive review of the HOs will be conducted to determine if the NSF grant should be renewed. Although the scientific products of the HOs will be limited at this point, this should be sufficient time to see if HOs are attracting the degree of interest from the research community that was anticipated. (A similar review must be done of the third through fifth HOs with the appropriate lag times.)

15.5.3 CUAHSI Management

The proposals for HOs must include a management plan at both the site and network level. These management plans must provide a mechanism for community input and oversight. CUAHSI will prepare such a management

plan and post it on its website. Any group preparing a proposal for HOs may download this management plan and include it in its proposal. CUAHSI will not endorse any proposal nor make any judgment about the suitability of a site as an HO or the utility of the proposed core data collection. Such judgments will be made by NSF and its review panels.

If the successful groups choose to include the CUAHSI management plan, the group will be bound to use CUAHSI management as a condition of its award. In the pilot phase of the HO, CUAHSI will be a “collaborator” with the groups operating the HOs. In other words, NSF will administer awards to CUAHSI and the universities separately from each other and directly to each party; no sub-awards are involved. CUAHSI will advise NSF as to whether the HO operation is satisfactory, or, if it is not, whether sufficient corrective actions have been taken. NSF is free to act on or to ignore this advice.

Upon renewal of the NSF award, it is possible that NSF will award a cooperative agreement to CUAHSI for operation of the HOs. CUAHSI will then make subawards to universities for HO operation. CUAHSI would then assume responsibility for oversight of the grants administration and for ensuring successful operation of HOs.

APPENDIX A. CAPITAL EQUIPMENT BUDGET ESTIMATE

(The section numbers in this section correspond to chapter numbers in the report)

(Some budgets in this section include annual operating costs, and are not included in the capital budget summary, but are included in the annual operating budget in Appendix B)

4. Stream Gauging and Overland Flow

Per-gauge cost estimates for collection of discharge data were obtained from the Raleigh NC office of the USGS (Jeanne Robbins, chief, data section, pers. comm., 7/8/03). Installation costs are approximately \$18,000 for a standard stage-discharge site (no backwater, pressure transducer measurement of stage) and \$25,000 for a site with backwater (AVM or ADCP equipment). Annual operating costs are approx. \$12,000 per site. These estimates were applied to the design above which calls for 53 new river/stream discharge gauging sites. It was assumed that 12 sites would have backwater conditions (the inlets to Falls Lake, Lake Benson, and Lake Wheeler, and 9 sites near the estuary). Using the upper end of the cost range for installation costs, total costs are estimated at:

The following cost estimate assumes that each of the three non-urban field sites will be co-located with a soil moisture/hydrometeorology measurement site. Costs are only included for measurements specific to the activities discussed in this section. Each of the three sites is priced as a stand-alone site. This estimate does not include costs associated with land leasing, which are included in the operations budget.

Costs associated with installing new stream gauging sites are assumed included in the stream gauging budget. This budget assumes 12 storm-sewer flow monitoring sites, and 20 non-sewer monitoring locations, which could include hydraulic controls such as drop inlets, culverts, bridge crossings, grade control structures, or slope-area rating curve sites. Data

Table A.4.1 Stream Gauging Costs

CLASS	QTY	DESC.	UNIT PRICE	EXT. PRICE
STREAM GAGES	42	No backwater effects	\$18,000.00	\$756,000.00
	12	Backwater effects	\$25,000.00	\$300,000.00
TOTAL CAPITAL COSTS				\$1,056,000.00
ANNUAL COSTS	54	Operations: Rating curve, maintenance, telemetry, repairs	\$12,000.00	\$648,000.00
TOTAL ANNUAL OPERATING COSTS (Incl. in Appendix B)				\$648,000.00

Table A.4.2 HO-wide “compare/contrast” overland flow measuring equipment

CLASS	QTY DESC.	UNIT PRICE	EXT. PRICE
SENSORS	6 Irrigation flow meters	\$1,200.00	\$7,200.00
	15 Welded aluminum H-flume	\$900.00	\$13,500.00
	30 Water level sensors, In-situ MiniTroll or equiv.	\$700.00	\$21,000.00
	3 Machined weirs, installation supplies, pipe, tubing	\$8,000.00	\$24,000.00
	12 1 liter capacity tipping bucket gage, shop made	\$600.00	\$7,200.00
DATA LOGGERS	18 CR10X Direct Display	\$280.00	\$5,040.00
	18 CR10X Serial connector and SC12 cable	\$85.00	\$1,530.00
Water Sampler	6 ISCO 6712 or equiv. W/ 24 sample bottles.	\$3,215.00	\$19,290.00
	1 LOGGERNET, multi-site data collection scheduling	\$395.00	\$395.00
INSTALLATION	18 Waterproof Enclosure, 16"x18"	\$270.00	\$4,860.00
POWER	18 Regulated Power Supply	\$300.00	\$5,400.00
	18 20 Watt Solar Panel, with mounting brackets	\$350.00	\$6,300.00
TRANSMISSION	3 Phone Modem (assuming direct phone connection)	\$340.00	\$1,020.00
	Options: Radio = \$420; Cell = \$520; + \$20-\$200 for antenna		
SHIPPING	1 Estimated Freight Shipping	\$500.00	\$500.00
	TOTAL		<u>\$117,235.00</u>

Table A.4.3. Overland flow monitoring station equipment for developed/undeveloped paired basin field sites.

CLASS	QTY DESC.	UNIT PRICE	EXT. PRICE
SENSORS	12 ISCO 2150 Flow meter (or equiv.) for meas. storm sewer flows Includes: velocity Area Module, battery module, velocity sensor	\$3,495.00	\$41,940.00
	20 Water level sensors (In-Situ Minitroll or equiv. With int. data logg	\$700.00	\$14,000.00
	12 Installation supplies, pipe, tubing	\$2,000.00	\$24,000.00
	2 Field wizard data shuttle for ISCO	\$1,795.00	\$3,590.00
SHIPPING	1 Estimated Freight Shipping	\$500.00	\$500.00
	TOTAL		<u>\$79,940.00</u>

telemetry is not included, but is included in the data communications budget (A.14). All sensors include data loggers. This budget also assumes that rainfall measurements will be made by the observatory precipitation network.

5. Precipitation

In this section we estimate the cost of the proposed network. The cost includes only the hardware. Annual maintenance costs, assumed 10% of capital cost, are included in the operations budget. Technician time and engineering will be included in the HO staff requirements, and

advanced engineering assistance is assumed to be available from the HMF. The entire cost of the system should also include the cost of software development (algorithms, data quality control, database design and development, visualization utilities), installation, and testing. The estimate excludes the administrative cost as well.

Experimental Activities. The cost includes adding 100 double-gauge platforms to different locations around the basin. The cost per platform is about \$4K and includes material, instruments, dynamic instrument calibration, cell modems, assembly, transportation (or shipment) and field deployment. The total cost is \$400K of

TABLE A.5 Precipitation measurements network capital equipment cost estimate.

Class	Quantity	Description	Unit Price	Ext. Price
Sensors	100	double-gage rain gage platforms with data loggers, power, and cellular modems	\$4,000	\$400,000
	4	Optical distrometers (three installed plus one spare)	\$5,000	\$20,000
	1	Multi-frequency atmospheric profiler	\$200,000	\$200,000
	4	X-band, polarimetric weather radars, cost includes deployment, and software	\$275,000	\$1,100,000
				<u>\$1,720,000</u>

capital investment. The four (three installed plus a spare) optical disdrometers cost approximately \$5,000 each. Multifrequency profilers cost approximately \$200,000. These costs are based on actual experience with similar systems developed and/or operated by W. Krajewski at the University of Iowa (www.iuhr.uiowa.edu/~iavalidate).

Polarimetric Radar Network. This item (4 X-band polarimetric radars) is estimated to cost \$1.1M. The cost includes deployment and partial software development. The estimate is based on the official quote obtained by one of the design team members (W. Krajewski) while preparing a proposal for the NSF MRI program.

Based on the above, we estimate with annual maintenance costs at \$172,000. (10%) of capital cost, and are included in the operations budget.

6. Energy Budgets, Evapotranspiration, and Land-Atmosphere Exchange (single site)

Estimates are per tower-site, assuming 25 sites. Additional sites could be added to better characterize vegetation/LULCC combinations.

Note that the pricing in this section assumes cost savings by collocation of instruments, e.g. shared loggers, equipment enclosures, tripods, rain gauges, power supplies, transmission equipment, etc.

7. Soil Moisture, Recharge, and Groundwater (single site)

The following equipment are needed to measure groundwater recharge, and will be co-located with flux towers (see Ch. 6), meteorological stations, and within the more extensive soil moisture sampling networks. The estimate includes sensors and data logging instrumentation. We will install the ETR suite in upland, mid-slope and bottom slope/riparian zones along a set of transects within six medium resolution watersheds (18 ETR suites, total). The heat dissipation sensors are for the regional soil moisture network.

8. Groundwater Exchange with the Neuse Estuary

Geochemical Approach

Sampling stations located along approximately 10 cross-estuary transects will provide the necessary spatial coverage to evaluate regions of elevated groundwater interactions. Approximately 30-40 stations within the estuary will be established.

Hydrographic measurements and samples for tracer analyses (surface and bottom waters) will be collected at each site. Water samples for tracer/nutrient analyses will also need to be collected from groundwater wells within the watershed (see below). These groundwater samples will

Table A.6.1: Eddy covariance and radiation budget stations (25 sites within Neuse River HO)

CLASS	QTY	DESC.	UNIT PRICE	EXT. PRICE
EQUIP.	1	CSAT3 Sonic anemometer	\$8,100.00	\$8,100.00
	1	LICOR 7500 H2O/CO2 open path gas analyzer	\$12,100.00	\$12,100.00
	1	Kipp & Zonen net radiometer	\$5,500.00	\$5,500.00
	1	LICOR LI-190SA Quantum solar radiation sensor (PAR)	\$400.00	\$400.00
	1	Air temp. R.H. probe Campbell Sci HMP45C	\$600.00	\$600.00
	5	Soil heat flux plates	\$200.00	\$1,000.00
	6	Nonlinear thermistors	\$83.33	\$500.00
	1	Campbell 23X data logger	\$3,000.00	\$3,000.00
	1	Cellular modem	\$350.00	\$350.00
	1	Small trailer or container (air conditioned)	\$8,000.00	\$8,000.00
	1	misc. calibration gases, lab/computer supplies	\$5,400.00	\$5,400.00
	1	tower, 3-column, with interior ladder and harness	\$18,000.00	\$18,000.00
	INSTALL.		Installation (est. at 20% of equip cost):	
		Electrical service		\$10,000.00
TOTAL CAPITAL COST PER FLUX TOWER				<u><u>\$85,540.00</u></u>

Table A.6.2: Canopy and leaf-level measurements. Two of each system will be acquired for the Neuse River HO

CLASS	QTY	DESC.	UNIT PRICE	EXT. PRICE
EQUIP.	1	LICOR LAI-2000, measures plant area density	\$5,000.00	\$5,000.00
	1	LICOR LI-6400 portable photosynthesis system, gas exch. Rates	\$20,000.00	\$20,000.00
	1	NA-1500; Carlo-Erba Strumentazione, Milan Italy, Measures N	\$100,000.00	\$100,000.00
		COST ESTIMATES NOT AVAILABLE!!!		
	1	Soil N measurement instrument??	\$4,000.00	\$4,000.00
INSTALL.		Installation (est. at 20% of equip cost):		\$25,800.00
TOTAL CAPITAL COST PER CANOPY/LEAF SYSTEM				<u><u>\$154,800.00</u></u>

be collected quarterly for the first two years. Total number of analyses for each tracer will be approximately 1200 estuarine, 150 groundwater, and 400 porewater samples. Total cost for this ~2-year geochemical component, assuming the necessary laboratory equipment is available, would be approximately \$250,000.

Physical Approach

The regional/watershed wells should be installed early in the project. The number of wells necessary is dependent on the number of publicly

available wells for monitoring water height and collecting groundwater samples. It is estimated that approximately 10 wells <50 meters below ground surface will need to be installed. Ideally, these wells would be equipped with a continuous water-level monitoring device that would reduce technician time. Water level in wells should be measured at least monthly during the first 2 years and at least quarterly thereafter. Local scale well fields will be constructed following the initial geochemical evaluation. This will provide some insight into areas of potentially higher groundwater discharge. Geochemical measurements from these

Table A.6.3: Atmospheric profiling systems. These instruments will be powered from the nearby trailer as in Table A.6.1. Five of these systems will be deployed through the Neuse.

CLASS	QTY	DESC.	UNIT PRICE	EXT. PRICE
EQUIP.	1	SODAR, vertical and longitudinal ABL velocity statistics	\$50,000.00	\$50,000.00
	50	Radiosondes	\$1,250.00	\$62,500.00
INSTALL.		Installation (est. at 10% of equip cost):		\$11,250.00
TOTAL CAPITAL COST PER ABL SYSTEM				<u>\$123,750.00</u>

Table A.7.1 Recharge Array

CLASS	QTY	DESC.	UNIT PRICE	EXT. PRICE
EQUIP.	1	Vadose Zone Array	\$20,000.00	\$20,000.00
	1	Groundwater Array	\$19,000.00	\$19,000.00
	10	Heat dissipation sensors	\$120.00	\$1,200.00
INSTALL.		Installation (est. at 20% of equip cost):		\$8,040.00
TOTAL CAPITAL COST				<u>\$48,240.00</u>
ONE TIME ANAL.	2	³ H/ ³ He analyses	\$700.00	\$1,400.00
	2	CFC analyses	\$300.00	\$600.00
	2	SF ₆	\$300.00	\$600.00
	2	¹⁴ C analyses	\$600.00	\$1,200.00
TOTAL COSTS OF CHARACTERIZATION ISOTOPIC ANALYSES				<u>\$3,800.00</u>
TOTAL RECHARGE ARRAY (each):				<u>\$52,040.00</u>

Table A.7.2 Observatory-Wide Soil Moisture Measurement Network

CLASS	QTY	DESC.	UNIT PRICE	EXT. PRICE
SENSORS	250	SM Vitel Probes, 0-2.5V, 25 ft cable length	\$349.00	\$87,250.00
	50	Apogee Precision IRT	\$650.00	\$32,500.00
	50	CR10X Direct Display	\$280.00	\$14,000.00
	50	CR10X Serial connector and SC12 cable	\$85.00	\$4,250.00
	1	LOGGERNET, multi-site data collection scheduling	\$395.00	\$395.00
SHIPPING	1	Estimated Freight Shipping	\$500.00	\$500.00
TOTAL			\$2,259.00	<u>\$138,395.00</u>

Table A.10 Sediment Transport and Geomorphology Capital Costs

CLASS	QTY	DESC.	UNIT PRICE	EXT. PRICE
	1	3-D laser topographic scanner (need verification)	\$80,000.00	\$80,000.00
	1	10 m research vessel for use in Lower Neuse & estuary w/winch	\$80,000.00	\$80,000.00
	2	6 m flat bottom bay boat for use in smaller channels/wetlands	\$15,000.00	\$30,000.00
	3	Multi-beam acoustic profilers with boat mounting hardware	\$12,000.00	\$36,000.00
	2	Laser diffraction system (LS-Series) by Beckman Coulter	\$58,000.00	\$116,000.00
	20	ISCO 6712 24 bottle samplers with level sensor and doppler velocity sensors.	\$4,440.00	\$88,800.00
		Surveying equipment: total stations, DGPS, levels, tripods		\$50,000.00
	3	Bed load samplers, BM54	\$700.00	\$2,100.00
	2	Seive sets with shaker	\$4,046.00	\$8,092.00
	2	Manual core sampler	\$700.00	\$1,400.00
	4	Computers for storage/processing of LIDAR and other topo data	\$4,000.00	\$16,000.00
	4	Laptop computers for field data acquisition	\$3,000.00	\$12,000.00
	1	Estimated Freight Shipping	\$5,000.00	\$5,000.00
		TOTAL		\$525,392.00

Table A.11 Costs Associated with Social Sciences Data

CLASS	QTY	DESC.	UNIT PRICE	EXT. PRICE
CENSUS DATA	3	Secure/update census block and other broadly available data for profiling the watersheds being studied and defining populations to be sampled (months)	\$3,500.00	\$10,500.00
DATA COLLECTION		Survey printing, handling, postage		\$1,500.00
SURVEY PROCES	2400	Survey process through data cleaning and recording (2400 surveys)	\$27.92	\$67,000.00
DATA ANALYSIS	3	Data analysis and estimations for the study watersheds (months)	\$3,500.00	\$10,500.00
P.I.	3	Social Scientist PI to oversee sampling process (months)	\$5,000.00	\$15,000.00
		TOTAL SOCIAL SCIENCE SURVEY COSTS		\$104,500.00

Note: These costs are included in the operations budget.

sites will then coincide with estuarine sampling over the remaining period (~2 years). Total cost for this 2-year physical hydrogeologic component would be approximately \$150,000.

Modeling Approach

The costs for the modeling component are primarily a function of technician/modeler time. Approximately \$65,000 is required. Total cost for quantification of groundwater discharge to

the Neuse Estuary over 2 year period, including construction of mathematical model and wells for future long-term monitoring, is approximately \$465,000.

9. Water Quality

For water quality laboratory equipment, the capital costs (\$350,000) and installation costs (\$35,000) were an estimate for acquiring and setting up a few large instruments (an ICMS, nutrient analyzer, a carbon analyzer, 1-2 other

Table A.14 Data Communications Budget

CLASS	QTY	DESC.	UNIT PRICE	EXT. PRICE
DATA/COMM	20	Battery operated cellular modem (Mode A)	\$4,500.00	\$90,000.00
EQUIP.	20	A.C. powered cellular modem (Mode B)	\$350.00	\$7,000.00
TOTAL CAPITAL COST				<u>\$97,000.00</u>
ANNUAL COSTS	54	DSL Wireless access (assumes DSL \$35.00/month)	\$420.00	\$22,680.00
	120	Cellular modem access points/accounts (\$18.00/month)	\$216.00	\$25,920.00
	6	T1 line lease, \$750/mon each.	\$9,000.00	\$54,000.00
TOTAL ANNUAL OPERATING COST				<u>\$102,600.00</u>

large instruments). This amount also includes ancillary laboratory equipment (analytic balances, muffle furnace, etc.) There was never any more specific breakdown for this. This is the \$385,000 (capital+installation) that is shown in the capital equipment summary budget.

10. Sediment Transport and Geomorphology

This budget assumes that the costs associated with operation of this equipment are borne by the operations budget of the observatory. It also assumes that the expenses associated the collection of LIDAR data are considered observatory-wide expenses and are not included in this specific budget.

11. Social Sciences Survey Data

Note: These costs are included in the operations budget.

12. Remote Sensing

We anticipate that CUAHSI will establish collaborative agreements with NASA and other government agencies for the free exchange of government remote sensing data. For the acquisition of non-governmental remote-sensing data, a modest budget of \$50,000 per year should

suffice. This does not include LIDAR data, which are included elsewhere in the operations budget. All remote sensing data acquisition costs appear in the operations budget.

13. Modeling

Modeling from the HO operations perspective is intended to produce additional data through synthesis of field data collection. The actual production of models and analysis of their output is an operations issue, with the HO providing a linkage with P.I. research. The capital equipment needs for this item are limited to computational and data storage and backup. The capitol equipment budget includes a request for \$70,000 for this purpose.

14. Data Communications

Note: data telemetry costs are already included in the stream gaging budget (54 sites). The rain gage network includes mode A cell modems (100 sites). The cost of the cellular modem hardware is included in the flux tower budget, but not data communications. Communications costs in terms of annual expenditures are shown below for the entire network, and are equal to approximately \$103,000 per year, and are included in the operations budget..

Total Capital Equipment Cost Estimate

Table A.15 Total Capital Equipment Cost Estimate

TABLE No.	QTY	DESC.	UNIT PRICE	EXT. PRICE
A.4.1	1	Stream gaging network (54 gages total)		\$1,056,000.00
A.4.2	1	HO-wide "compare/contrast" overland flow measurement eq.		\$117,235.00
A.4.3	1	Overland flow equip. for paired basin sites		\$79,940.00
A.5	1	Precipitation measurement network		\$1,720,000.00
A.6.1	25	Eddy covariance/net radiation stations	\$85,540.00	\$2,138,500.00
A.6.2	2	Canopy and leaf-level measurement suites	\$154,800.00	\$309,600.00
A.6.3	5	Atmospheric profiler systems (SODAR) + radiosondes	\$123,750.00	\$618,750.00
A.7.1	18	Recharge array (co-located with flux some flux towers)	\$52,040.00	\$936,720.00
A.7.2	1	HO-wide soil moisture measurement network		\$138,395.00
A.8.2	1	Geochemical observations of groundwater/estuarine exch.		\$250,000.00
A.8.3	1	Physical monitoring of groundwater exchanges with estuary		\$150,000.00
A.8.4	1	Modeling to predict groundwater exchanges to estuary		\$465,000.00
A.9	1	Water quality laboratory equipment and installation		\$385,000.00
A.10.1	1	Sediment transport and geomorphology		\$525,390.00
A.13	1	Modeling (computers, input/output, data storage/backup)		\$70,000.00
A.14	1	Data communications		\$97,000.00
TOTAL CAPITAL COST				<u><u>\$9,057,530.00</u></u>

APPENDIX B. HO OPERATIONS BUDGET

Salaries (based on 14 July 04 meeting at Duke)

- 7 FTE field technicians
- 2 FTE lab technicians
- 2 FTE database management, web site
- 2 FTE administrative assistants
- 1 FTE director
- total 14 FTE, avg. salary+fringe benefits=\$100,000/year
- Also included are 20 student laborers, \$20/h (sal+f.b.), 400 hours total each

Table B.1 Annual Operating Expenses Estimate

CLASS	QTY	DESC.	UNIT PRICE	EXT. PRICE
SALARIES	14	FTE as described above	\$100,000.00	\$1,400,000.00
	20	Student labor, 20 students, \$20/h (s+fb), 400 h each	\$8,000.00	\$160,000.00
OPERATING EXPENSES & MAINTENANCE	1	Social Sciences Annual Studies (From table A.11.1)	\$104,500.00	\$104,500.00
	1	Acquisition of remote sensing data from private companies	\$50,000.00	\$50,000.00
	54	Streamgaging annual operating costs (from table A.4.1)	\$12,000.00	\$648,000.00
	1	Overland flow maint/repair (10% of table A.4.2+A.4.3)	\$20,000.00	\$20,000.00
	1	Precip network maintenance/repair (10% of table A.5)	\$172,000.00	\$172,000.00
	25	Energy budget network maint/repair (10% of table A.6.1)	\$8,550.00	\$213,750.00
	2	Canopy/leaf scale maint/repair (10% of table A.6.2)	\$15,480.00	\$30,960.00
	5	ABL maintenance/repair (10% of table A.6.3)	\$12,375.00	\$61,875.00
	18	Recharge network maint/repair (10% of A.7.1)	\$5,200.00	\$93,600.00
	1	Soil Moisture network maint/repair (10% of A.7.2)	\$13,800.00	\$13,800.00
	1	Water qual. Lab operations/maint/repair (10% of A.9)	\$35,000.00	\$35,000.00
	1	Sediment/Geomorphology maint/repair (10% of A.10)	\$53,000.00	\$53,000.00
	1	Data Comm. annual expenses (from table A.14.1)	\$102,600.00	\$102,600.00
	50	Radiosondes	\$1,250.00	\$62,500.00
	11	Staff training	\$4,000.00	\$44,000.00
LIDAR DATA	500 sq. miles per year at (\$300/ sq. mi)		\$300.00	\$150,000.00
FACILITIES	6000	HO Main Office/Lab, 6000 sq. ft at \$20/sq. ft/year	\$20.00	\$120,000.00
	4000	Field staging areas, 2 ea, 2000 sq. ft, \$10/sq.ft/year	\$10.00	\$40,000.00
	1200	Storage (boats/equip.) 1200 sq. ft/, \$10/sq.ft/year	\$10.00	\$12,000.00
	10000	Utilities (\$2.00/sq.ft/year)	\$2.00	\$20,000.00
	360	Agricultural (non-tobacco) land lease, \$200.00/acre/year	\$200.00	\$72,000.00
	120	Forested land lease, \$50/acre/year	\$50.00	\$6,000.00
		Telephone/fax/postage		\$8,000.00
VEHICLES	5	3/4 ton pickup rental, \$260/mo*12mo/yr=\$3120/yr	\$3,120.00	\$15,600.00
	5000	Gasoline (20,000 mi/veh/year, 20 mpg,)=5000 gal	\$2.00	\$10,000.00
	1	Boat dockage and maintenance (\$200/mo)	\$2,400.00	\$2,400.00
	100000	Vehicle repairs (\$0.04/mi)	\$0.04	\$4,000.00
	100000	Reimburseable mileage (\$0.37/mi)	\$0.37	\$37,000.00
TOTAL ANNUAL OPERATING COST ESTIMATE				\$3,762,585.00