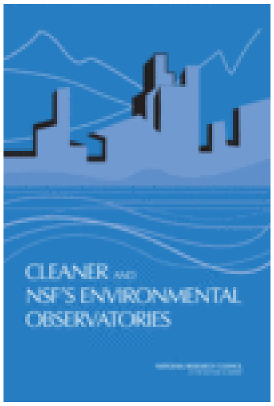

CLEANER and NSF's Environmental Observatories

Committee on the Collaborative Large-Scale Engineering Analysis Network for Environmental Research (CLEANER), National Research Council

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CLEANER AND NSF'S ENVIRONMENTAL OBSERVATORIES

Committee on the Collaborative Large-scale Engineering Analysis Network for Environmental Research (CLEANER)

Water Science and Technology Board

Division on Earth and Life Studies

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* The activities of this committee were overseen and supported by the National Research Council's Water Science and Technology Board (see Appendix A for listing). Biographical information on committee members is contained in Appendix B.

Preface

Environmental engineers and scientists have long worked to understand better the interactions between humans and their natural and built environments and how they affect each other. These relationships become increasingly important as growing urban populations and economic development degrade the quality of environmental resources and alter the types and functioning of ecosystems. With an increasing interest in the sustainable use of natural resources, the recognition of society's dependence on ecological goods and services, and the perceived long-term continuing decline of the quality of our air, land, and water resources, it becomes increasingly important to prevent irreversible damage to the environment and its ecosystems. We must improve our understanding of environmental processes in order to predict the likely impacts resulting from alternative environmental resource management policies and practices.

The quality of our environment is influenced by both natural forces and human activities. To better understand and predict future conditions under alternative resource management strategies and human influences, many engineers and scientists believe that an improved research infrastructure is needed to observe the characteristics, processes, and phenomena that take place in our natural and built environments over short temporal and broad spatial scales. In response to this perceived need, the National Science Foundation (NSF) is considering establishing several types of observatory networks.[1] These observatory networks are to provide improved capabilities for near real-time dynamic monitoring, modeling, and analysis of hydrologic and ecological processes. A common goal of these networks is to advance our understanding of complex environmental systems, thereby enhancing our overall predictive capacities and adaptive management approaches.

Environmental observatory networks are believed to be critical for addressing the primary environmental challenge for today's society: to more fully understand the functioning of our present and future ecosystems and to find more effective ways of sustaining the supply and quality of environmental resources and ecological goods and services provided by those systems. At the core of this challenge is the need to better understand the interactions within and among the atmospheric, hydrologic, geophysical, ecological, and human components of our environment. To accomplish this will require networks of

[1] These networks include the Collaborative Large-scale Engineering Analysis Network for Environmental Research (CLEANER), the Consortium of Universities for the Advancement of Hydrologic Science, Incorporated (CUAHSI) Hydrologic Observatories, the National Ecological Observatory Network (NEON), the Geosciences Network (GEON), the Ocean Observatory Initiative (OOI), and the Arctic Observing Network.

various field and remote measurement devices in communication with computer systems for data compilation, storage, and analyses. Together these network components must be able to transform a patchwork of local measurements into a comprehensive integrated picture of the coupled environmental-human system.

These proposed environmental observatory networks would enhance opportunities for research on environmental-human interactions and processes. Coordinated multi-disciplinary data sensing, monitoring, collection, and modeling strategies could lead to a more comprehensive vision of how best to assess, forecast, manage, and protect complex environmental resources over temporal and spatial scales not presently assessed.

The committee of scientists and engineers with expertise in environmental engineering, hydrology and hydrogeology, ecology, coastal and marine science, computer science, and economics that wrote this report was organized by the National Research Council (NRC) and charged to advise the NSF on the Collaborative Large-Scale Engineering Analysis Network for Environmental Research (CLEANER) initiative's science plan. It was also asked to comment on the overall value of networked environmental observatory facilities for improving our understanding of complex water resource systems. While we focus mainly on water, as charged, we cannot help but also consider the effects that managed water quantity and quality regimes have on natural ecosystem functioning and human activities. Any study of those effects must be based on ecosystem and social impact data, as well as hydrologic and environmental data. An improved ability to predict the interactions among natural environmental and human systems will require integrated sets of hydrologic, environmental, ecosystem, and social science data. These data must be collected over the temporal and spatial scales in which important human-environmental interactions take place.

Our study period lasted only several months. In preparation for our first and only meeting in late 2005, committee members provided in advance written material relevant to the assignment. At our meeting we were briefed by NSF representatives on the current status and long-term plans for CLEANER and other (CUAHSI and NEON) associated networked observatories. Following the meeting, all members of the committee participated in the development of this report. The report represents a consensus of all committee members with respect to our findings and recommendations.

We are grateful to Patrick Brezonik, Douglas James, and Elizabeth Blood from the NSF who contributed to our understanding of relevant NSF goals, constraints, activities, and plans concerning observatory initiatives. The committee hopes the advice we provide in this report proves useful as they and their colleagues proceed with the planning and implementation of these observatory programs.

As chair, I thank all committee members for their thoughtful and timely contributions to this review in what surely must be among the shortest duration and more intense studies of the NRC. On behalf of our entire committee I also thank our project manager Dorothy Weir, Research Associate with the Water

Science and Technology Board, and the Water Science and Technology Board's Director, Stephen Parker. They organized the overall effort from beginning to end, managed all communications, and dealt with all the usual and numerous logistical details. We thank them both for their contributions to our deliberations and development of this report.

This report has been reviewed in draft form by individuals chosen for their diverse perspectives and technical expertise, in accordance with procedures approved by the NRC's Report Review Committee. The purpose of this independent review is to provide candid and critical comments that will assist the NRC in making its published report as sound as possible and will ensure that the report meets institutional standards for objectivity, evidence, and responsiveness to the study charge. The review comments and draft manuscript remain confidential to protect the integrity of the deliberative process. We wish to thank the following individuals for their review of this report: Dr. Patrick R. Atkins, Aluminum Company of America; Dr. Chaitanya K. Baru, University of California, San Diego; Dr. Kenneth R. Bradbury, Wisconsin Geological and Natural History Survey; Dr. George M. Hornberger, University of Virginia; Dr. Perry L. McCarty, Stanford University; Dr. Patrick J. Mulholland, Oak Ridge National Laboratory; and Dr. Leslie L. Shoemaker, Tetra Tech, Inc.

Although the reviewers listed above provided many constructive comments and suggestions, they were not asked to endorse the conclusions or recommendations, nor did they see the final draft of the report before its release. The review of this report was overseen by Dr. Diane M. McKnight of the University of Colorado. Appointed by the NRC, she was responsible for making certain that an independent examination of this report was carried out in accordance with institutional procedures and that all review comments were carefully considered. Responsibility for the final content of this report rests entirely with the authoring committee and the institution.

Daniel P. Loucks, *Chair*

Contents

Summary

Degradation of our nation's water resources threatens the health of humans and the functioning of natural ecosystems. To better understand the causes of these adverse impacts and how they might be more effectively mitigated, especially in urban and human-stressed aquatic systems, the National Science Foundation (NSF) has proposed the establishment of a Collaborative Large-scale Engineering Analysis Network for Environmental Research (CLEANER) to: provide an efficient, common platform for near real-time and conventional observation, data storage, data distribution, data analysis and modeling of large-scale environmental and hydrologic systems, including urban and human-stressed systems; improve our understanding and prediction of hydrologic, environmental, engineering, and ecological processes controlling these systems over a range of spatial and temporal scales; elucidate human-induced impacts on the environment; and identify more effective adaptive-management approaches to mitigate adverse impacts of human activities on water and land resources.

As part of the development of the CLEANER science plan, the NSF sought the advice of the National Research Council (NRC) on the "grand challenges" to be addressed by the network, especially those related to water, and on the value of observatory networks in general. In response to the NSF's request, the NRC's Water Science and Technology Board assembled a committee having expertise in a broad set of relevant disciplines to carry out the tasks shown in Box S-1.

CLEANER AND THE OBSERVATORY APPROACH

The justification for a CLEANER environmental observatory network derives from our current inability to sufficiently understand large-scale environmental processes and thereby develop more effective management strategies. First, we lack basic data and the infrastructure required to collect these data at needed temporal and spatial resolutions. Second, even with such data, further research is needed in data integration across scales from different media and sources (observation sensors, laboratory experiments, model simulations). Third, because of the lack of long-term, large-scale integrated data we lack a sufficient understanding of many underlying processes that take place over various space and time scales. The collection and analysis of such data should make it possible to better understand environmental processes that operate over large spatial scales or for long time periods and to determine how those processes affect humans and how humans affect those processes. This in turn should result in the development of more accurate models and decision support systems for predicting the effects of different management strategies on society and water resources.

BOX S-1
Statement of Task

A committee formed by the Water Science and Technology Board (WSTB) will advise the National Science Foundation on its Collaborative Large-Scale Engineering Analysis Network for Environmental Research (CLEANER) initiative with respect to (1) the science plan and (2) the potential usefulness of the program. Regarding the science plan, the WSTB will identify some (5-6) of the major issues in the area of water quality and water resources that present "grand challenges" and that lend themselves to being addressed by CLEANER, i.e., perhaps providing the targets for observation and modeling efforts. Regarding the second issue, the WSTB will comment on the overall value to engineering and other potentially interested disciplines of networked environmental observatory facilities to improve our understanding of complicated, large-scale water quality and water resources problems and the development of cost-effective engineering approaches to their solution. The scope of issues to be considered by the WSTB will be limited to water quality and water resources; i.e., air will only be considered to the extent that it affects water. Note that for purposes of this study, a "grand challenge" is defined to mean a major scientific and/or technological task that is compelling for both intellectual and practical reasons, that offers potential major breakthroughs on the basis of recent developments in science and technology, and that is likely to be feasible given current capabilities and a serious infusion of resources.

Some examples of the types of investigations these environmental observatory networks should make possible include:

1. how and the extent to which ecosystem processes contribute to the human economy;
2. the influence of water quality and quantity on ecosystem structure and function and, in turn, on engineering requirements and environmental decision making;
3. the effects of climate change on the characteristics of aquatic systems;
4. the ways in which human economic activities, including urbanization, affect hydrologic processes and ecosystems;
5. the changes in types, amounts, and impacts of pollutants on the quality of our environment and on ecosystem functioning and human health;
6. how land and water use changes in response to both physical and social conditions; and
7. the propensity of global climate change to propagate waterborne diseases.

Many of these investigations will motivate and facilitate needed research on how to better integrate and use social, physical, chemical, and biological data within predictive models.

Finally, the results from these and other data collection and research activities could serve to substantially upgrade our environmental science and engineering educational and outreach programs. This would benefit current environmental protection and management programs, the public, and the next generation of scientist and engineers. These potential outcomes and contributions are the rationale for CLEANER.

GRAND WATER CHALLENGES AND RESEARCH QUESTIONS

To meet its potential, CLEANER must be planned and designed to address a variety of "grand challenges" in environmental sciences and engineering. The committee believes that the grand challenges presented in *Grand Challenges in Environmental Sciences* (NRC, 2001) are sound. Therefore, rather than identifying additional challenges, the committee presents research questions and issues that stem from these existing challenges and that address complex water-related problems requiring an observatory approach. These research questions and issues are grouped into three categories that are detailed below. The first category includes questions that address interactions among humans, the environment, and ecosystems to advance knowledge of phenomena and processes. The second category includes questions to understand and provide innovative engineering approaches that can improve water quantity and quality management to sustain a healthy economy. The third category includes research issues related to the design of CLEANER observatories and the development of tools and technologies that will make possible the collection of long-term data over large scales that are necessary to address the scientific questions and issues.

Interactions among Humans, the Environment, and Ecosystems

The research should aim to:

- better understand biogeochemical cycling in river and estuarine systems and how the cycles are influenced by human activities. Using continuous measurement technologies for measuring flow and solutes, processes in perturbed systems that cycle, for example, carbon, nitrogen, and phosphorus, can be understood in detail, evolving patterns of change can be detected, and strategies can be developed to mitigate adverse human impacts from urbanization and agricultural practices.

- determine the extent to which humans can alter their environment and its ecosystems while still sustaining desired levels of ecosystem function.

Large-scale environmental observatories can identify just how far humans can alter water regimes and landscapes before recovery cannot be economically achieved.

- learn how changes in climate, land cover, and land use affect water quantity and quality regimes and their impact on ecosystem health and other uses of water such as for drinking, irrigation, industry, and recreation. Using long-term data, comparative studies, modeling, and experiments, observatory systems can determine pathways of movement of water and solutes through human-dominated landscapes and forecast responses to changes.

Innovative Engineering Approaches for Improving Water Quantity and Quality Management

The research should aim to:

- improve our capabilities in hydrologic forecasting for water resource managers to evaluate and make decisions. Networks of sensors, robotic water quality monitoring sites, real-time data collection, and communication links can be developed into an intelligent environmental control system that will enhance the protection of urban ecosystems and the health and safety of its inhabitants. Such a system can be used as an early warning system and to identify emerging problems such as flooding, lack of water, riparian habitat degradation, and the presence of toxic compounds.

- find solutions to existing and emerging problems involving contaminants in the environment that affect ecosystems and human health. Some environmental problems that affect water resources are of such a magnitude that they are of national concern and require engineering research based on data collected through observatories. Two such problems are the containment or removal of contaminated sediments and the effects on aquatic and human health of residuals from pharmaceuticals and other household products.

Design of CLEANER's Environmental Observatories

Recommended research concerns the:

- use, deployment, and evaluation of multiple types of sensors for collecting comprehensive and integrated environmental data over large spatial and long temporal scales;

- development of the components of a robust and adaptable cyberinfrastructure that can link to other databases; and

- collection and use of social science data along with physical, chemical, and biological data needed to address environmental problems caused by human activities.

IMPLEMENTING ENVIRONMENTAL OBSERVATORIES

Planning and development activities are underway by the NSF for a series of national environmental observatory systems in the United States.[1] For example, the observatories considered by CLEANER will be focused on hydrologic and environmental science and engineering research issues. The observatories considered by NEON are focused on ecological research issues. These and other NSF environmental observatory networks each have somewhat different goals and missions, but there is also considerable overlap in terms of scope and components of research and outreach activities. Cooperation and collaboration among these different observatories should be beneficial to all research communities.

There are also other governmental (federal, state, local) environmental assessment programs that would supplement those of CLEANER. These programs are typically closely linked to the mission of the agencies. Just as it is important for CLEANER to be well integrated into the other applicable NSF environmental observatories, it also should be closely collaborating with the various federal, regional, state, and local monitoring and environmental assessment activities as well. To facilitate and improve linkages between CLEANER and existing governmental programs, inter-agency agreements and periodic workshops and other joint activities and interactions may be critical for successful long-term coordination and collaboration.

CLEANER is in a unique position to catalyze linkages between the national science-based observing systems and governmental environmental assessment efforts. If properly coordinated and managed, CLEANER could add considerable value to ongoing government efforts through data management and the application of models and other analysis tools. In turn, through proper coordination and linkages with other more science-based observatories, CLEANER can focus its resources more on the important engineering and underlying science issues that are of national significance.

[1] These networks include CLEANER, the Consortium of Universities for the Advancement of Hydrologic Science, Incorporated (CUAHSI) Hydrologic Observatories, the National Ecological Observatory Network (NEON), the Geosciences Network (GEON), the Ocean Observatory Initiative (OOI), and the Arctic Observing Network. In late 2004, NSF merged CLEANER and the CUAHSI Hydrologic Observatories into a single initiative called the Water Environmental Research Systems (WATERS) Network. Because the details of this merged activity were not fully resolved during the committee's study period, the report generally refers to the activity as "CLEANER," though the report recommendations should be relevant and useful to the developing WATERS Network.

CONCLUSIONS AND RECOMMENDATIONS

- The committee supports the concept of CLEANER and recommends that the NSF proceed with its planning, implementation, and intra- and interagency coordination activities. These activities should include the consideration by the NSF of an overarching parent organization that could be termed the "Environmental Observatory Networks" or EON. This parent organization could be responsible for cyberinfrastructure development, educational activities, outreach, and other shared activities across the NSF environmental observatory programs. EON would facilitate collaboration and coordination among the NSF observatory programs; the collection, management, and distribution of integrated data of value to all NSF programs; and reduce observatory program redundancy and costs.

- The NSF should also seriously evaluate the potential pitfalls of environmental observatory networks that might negate their many potential economic and scientific benefits. Some of these potential pitfalls or "fatal flaws" are lack of sufficient funding, especially that needed to maintain and upgrade the observatories; software security failures; inadequate planning of research projects; inadequate observatory geographical coverage; and inability to recruit and train engineers and scientists with the interdisciplinary breadth to address the future research challenges of CLEANER. The consideration of these possible scenarios can help identify and prevent potential "surprises" that could reduce the value of environmental observatories. Long-term integrated data derived from CLEANER's network should support fundamental engineering research and education on environmental problems in large-scale, human-stressed environments and ecosystems. An environmental observatory network has the potential to, and thus we believe should, transform the environmental science and engineering profession and its contributions to society.

- A successful environmental science and engineering observatory should:

  1. serve as a center of excellence in the development of new measurement capability and of new methods for data analyses;
  2. integrate measurements over different scales of space and time and ensure the constancy and quality of measurements;
  3. provide and support a robust data environment that facilitates the assessment of basic processes and principles and the development of new theory;
  4. provide a test bed for generating new applications including enhanced modeling and forecasting capabilities that support adaptive management decision-making; and
  5. motivate the transformation of environmental science and its relationship with other sciences.

- The development and implementation of CLEANER and other national environmental observatories presents an opportunity to recruit and train new generations of engineers and scientists in near real-time observation science and its application to management of water and other environmental resources.

- CLEANER should foster collaboration of engineers, scientists, government researchers, resource managers, policy makers, and community groups working across disciplines, across temporal and spatial scales, across different types of landscape surfaces and subsurfaces, and across watersheds/airsheds in different climatic regions. It should provide researchers and water resource managers with access to linked environmental sensing networks, data repositories, and computational tools for integrated assessment modeling, all connected through high performance computing and telecommunication networks. As a result of this collaboration, CLEANER should provide adaptive approaches for evaluating and forecasting regional environmental impacts, accounting for biological, chemical, physical, and human influences.

- The CLEANER network of data sets should be available to all researchers with permission from those who collected them. Data should be widely available and able to be shared among the research community. Open standards and data sharing can be critical to the ultimate success and long term success of CLEANER. The use of uniform data storage and centralized data repositories is a central challenge and opportunity for the program.

- CLEANER's integrated data sets, some of them available in near real-time, obtained from various remote and *in situ* sensors should facilitate the development of improved, process-oriented models that can be refined continually as new observatory data become available. This invaluable feedback loop should continually improve our understanding of processes in perturbed aquatic ecosystems.

- CLEANER observatory programs should span a range of increasingly human impacted regions including those having a fresh/marine water interface. A comprehensive network of sensors deployed in these contrasting regions is likely to shed new light on controlling and adaptively managing physical, chemical, biological, and geological processes. The program should identify vital sign indicators based on an understanding of current system conditions and expected trends and use these indicators for early warning and long-term predictions.

1
Introduction

The United States faces widespread problems associated with environmental resource degradation. Our air, land, and waters are subjected to multiple human-induced stressors that alter their quality. These disturbances in-turn lead to riparian ecosystem habitat loss, biogeomorphic landscape changes, changes in water availability, and increased discharges of a variety of pollutants over different temporal and spatial scales. All this is adversely affecting economic productivity, human health, and ecosystem functioning.

To help address our current environmental problems, we need an improved understanding of the fundamental processes that take place in large-scale human-stressed environments over long time periods. This better understanding can come from observing different environments at regional scales. We need to monitor and measure how the characteristics and functioning of environmental resources and ecosystems change and determine why they change to the extent they do. This new knowledge should lead to improved predictive models and to more effective adaptive management policies and practices. To accomplish this we need improved sensors and measurement technology that can provide high resolution and integrated data. This will require a cyberinfrastructure capable of collecting, managing, and using very large integrated data sets. Having this infrastructure will facilitate numerous research investigations aimed at obtaining an improved understanding of interacting environmental system processes.

Altered hydrologic regimes and increased pollutant concentrations in our air, soil, and water can adversely affect the quality of those resources, and their value to humans, as well as the functioning of natural ecosystems. We need to quantify these relationships so that the likely consequences of human decisions can be predicted and possibly valued. Because pollutants cycle between air, water, and land, we need to understand the interplay among these media and how efforts to control pollutants in one medium, say water, affect the quality in other media, say air or land. In addition, society needs more effective ways to select among management strategies (e.g., promoting the use of alternative materials versus developing enhanced waste treatment options) to address complex environmental problems and develop short-term strategies that satisfy long-term needs.

Contaminated water resources are a special concern, with major problems in large rivers (e.g., the Mississippi, the Hudson), coastal waters (e.g., Gulf of Mexico, Chesapeake Bay), groundwater aquifers (e.g., salt water intrusion along coastal aquifers), small streams (e.g., those receiving the sediments from mountain-top removal for coal mining or from poor agricultural or logging practices) and lakes of all sizes (e.g. those subjected to nutrient enrichment from development along their shores). Pathogenic microorganisms, such as *Cryptosporidium*, are common in the nation's waters and threaten public health. Organic chemicals and trace metals from municipal and industrial sources pose risks to human health and to aquatic organisms, as do pharmaceuticals and personal care products that increasingly are being detected in surface waters. Challenges to understanding and management are exacerbated by linkage to large-scale and long-term trends, such as global warming, economic globalization, and growing energy scarcity. These and similar observations in the U.S. and abroad have motivated the considerable attention given to the concept of environmental sustainability.

To help scientists, engineers, and managers better understand, model, forecast, and manage the quality of the environment and discover innovative approaches for its improvement, the National Science Foundation (NSF) has been planning several observatory networks designed to promote a greater understanding of hydrologic, environmental, ecological, and related processes affecting, and affected by, human activities. In particular, the Directorate for Engineering has proposed the Collaborative Large-scale Engineering Analysis Network for Environmental Research (CLEANER) to enable the identification of more effective adaptive management approaches for human-stressed environments based on enhanced observations, experiments, modeling, and engineering analysis. Other proposed networks include the National Ecological Observatory Network (NEON), being developed within the Directorate for Biological Science; the Hydrologic Observatories initiative fostered by the Consortium of Universities for the Advancement of Hydrologic Science, Incorporated (CUAHSI), the Ocean Observatories Initiative (OOI), and the Geosciences Network (GEON), which are supported by the Directorate for Geosciences; and the Arctic Observing Network of the Office of Polar Programs.

In late 2004, the NSF proposed the merger of CLEANER and CUAHSI's Hydrologic Observatories into a joint, bi-directorate program. The CLEANER and CUAHSI communities are currently collaborating to create a common science plan (targeted for completion in late 2006) for the merged activity, the Water Environmental Research Systems (WATERS) Network. Although all aspects of this merger were not fully resolved during the period of this study, which presented a "moving target" for our committee, this report has been written in an attempt to be useful and relevant to CLEANER, or the WATERS Network, or any observatory network focused on aquatic environments affected by human activities, or, and preferably, the integration of these different observatory initiatives. Generally, we refer to our subject matter as "CLEANER" but the report should be equally relevant to the WATERS Network.

CLEANER

CLEANER is to be an integrated network of environmental observatories supporting both fundamental engineering research and outreach and education on large-scale, water-related environmental problems in human-stressed environments. CLEANER observatory sites will likely be some combination of:

(1) large watersheds selected to represent a range of climatic, geomorphic, and land-use/land cover characteristics; (2) coastal sites; and (3) urban water systems. The watersheds (scale of about 10-30 thousand square kilometers) ideally would include the full range of human impacts from pristine or nearly pristine areas to heavily urbanized and agricultural lands. They would be instrumented in a nested arrangement to provide critical water-related information across a range of spatial scales from small to higher order (larger) catchments. The coastal sites would instrument important but threatened near-shore environments such as Chesapeake Bay, Tampa Bay, and coastal areas on the Great Lakes. Urban water observatories would provide water quality and quantity information on both the natural and engineered water systems in urban areas across a range of climatic zones. These urban areas would include their infrastructure for drinking water treatment and distribution, wastewater collection and treatment, and storm-water management (P. Brezonik, NSF, personal communication, 2006).

The proposed observatories would provide researchers with access to linked sensing networks, data repositories, and characterization and computational tools for integrated assessment modeling, connected through high-performance computing and telecommunications networks. CLEANER would potentially provide a comprehensive engineering approach to forecasting and evaluating regional environmental impacts, accounting for human influences on natural biological, chemical, and physical processes. Such an approach should lead to the establishment of cause-and-effect relationships with a feedback mechanism for implementing change through innovative engineering and policy interventions.

Origin

The CLEANER concept originated in 2001, and several workshops have been held at various universities since then to develop it further. This proposed program has been motivated not only by the need to better understand environmental–human interactions and impacts, but also by the increasing availability of new technology in sensors, communications, information management, and computing. This technology presents opportunities for learning how to better protect, restore, and manage the environment at spatial and temporal scales that have not been previously possible. Participants in the various workshops focused on the information needs of environmental scientists and engineers, and on how such information is to be obtained, managed, and converted to knowledge for the benefit of diverse groups of stakeholders, i.e., researchers, educators, policy makers, and the affected public.

The following key research elements for the CLEANER program emerged as a result of these early planning efforts:

- learning how hierarchies (scale and complexity) of human-stressed environmental systems and their linkages can be better understood through integrated assessment models;

- understanding the functioning of large-scale, complex, perturbed environmental systems by identifying the stressors that influence the outcomes of interactions among system components, based on frequent observations facilitated by real-time devices for sensing, data acquisition, data analysis, and data display;

- identifying vital sign indicators based on functional understanding, both for system condition and early warning; and

- learning how better to prevent and mitigate adverse environmental impacts and better manage stressed environmental systems.

Goals

CLEANER aims to create a network of observatories and an advanced cyberinfrastructure that will facilitate the collaboration of engineers, scientists, policy makers, and community groups working across disciplines, across temporal and spatial scales, and across different types of surface and subsurface environments in watersheds subjected to a range of climatic conditions. This collaborative work is to be focused on developing the ability to detect and respond effectively to rapid changes in system functioning, to implement near real-time decision-making supported by data collection that can be used to anticipate future problems, and to develop innovative and effective engineering solutions and management options.

Through CLEANER, the NSF seeks to "fundamentally transform and radically advance" the scientific and engineering knowledge needed to address the challenges of large-scale human-impacted complex environmental systems. CLEANER would focus on stressed environments and on water and associated environmental resources that are critical to economic productivity, human health, and quality of life. Predictive understanding of these changes can lead to more effective adaptive management approaches. CLEANER would provide a focus for developing and/or defining user needs, system architecture, high performance sensors, the operation of integrated sensor networks, and data handling protocols and standards. The coupling of these capabilities with advanced modeling would lead to greater integration of experimentation and simulation. CLEANER would provide access to databases that promote the development and validation of models by reducing the need to make assumptions about mechanisms, by narrowing the uncertainty in parameter values, and by providing better information about time variability of model parameters.

Specifically, the goals[1] of CLEANER are to:

- be an integrated system of distributed, networked facilities and researchers to more readily identify knowledge gaps related to environmental quality issues;
- enable the development of creative and effective engineering approaches to complex, national-scale environmental problems;
- consist of (a) interacting field sites networked through cyberinfrastructure; (b) groups of investigators studying landscapes stressed by human activities and/or highly urbanized regions; (c) specialized personnel, facilities, and technology that support the investigators, and (d) an analysis network with common modeling platforms and analysis protocols that will serve as the central organizational framework for collaborative investigations;
- support collection of critical environmental data with advanced sensor array systems and *in situ* instrumentation;
- facilitate data mining and aggregation and provide analytical tools for data visualization, exploratory data analysis, and predictive modeling of large-scale dynamic environmental management strategies;
- enable more effective adaptive management approaches for human-dominated environmental systems based on enhanced observations, experimentation, modeling, engineering analysis, and design;
- enable participation from a broad engineering and science community, including educators, students, practitioners, and public sector organizations and individuals, who will have access to CLEANER's equipment, data, models, and software; and
- transform engineering education and outreach by engaging the academic community and the general public in large-scale and complex real-world environmental management problems.

Status and Future Plans

The NSF Directorate for Engineering awarded $1 million in planning grants in 2004 for 12 projects,[2] involving principal investigators from 22 universities, to plan the system cyberinfrastructure and the nature of the field facilities that will constitute the network. A CLEANER project office was established in August 2005 to coordinate and assist with (1) refining the key science questions

[1] *http://www.nsf.gov/pubs/2005/nsf05549/nsf05549.htm*.
[2] Further information on these projects can be found on-line at *http://cleaner.nacse.org/partners/index.html*.

(grand challenges for environmental engineering) that CLEANER would address and (2) developing a unified community vision for the facilities and infrastructure needed to address these issues. A conceptual design that describes the research, education, and outreach plans will be a natural consequence of these activities. An important task of the CLEANER Project Office will be developing a community consortium that has the capability to plan, design, construct, and operate the CLEANER network.

As noted above, the NSF's Engineering and Geosciences Directorates are currently planning to combine CLEANER with the CUAHSI Hydrologic Observatories into what is now called the WATERS Network. This integrated program would move forward as a single initiative to be presented for Major Research Equipment and Facilities Construction (MREFC) funding in 2011. Initial construction of the network would shortly follow, and be completed and fully operational by 2015. This committee concurs with, and supports, the NSF in their efforts to develop a more unified community vision for environmental observatory facilities and infrastructure. Such integration brings both scientific benefits as well as economic cost savings.

SCOPE AND PURPOSE OF THIS REPORT

The Directorate for Engineering is developing the CLEANER program through a phased approach. The initial phase is to identify the science questions that the network seeks to address. Subsequent phases would involve selecting locations, and determining and building the infrastructure needed for the collection of data that will address these issues. As part of the initial preparation of the CLEANER science plan, the NSF sought the advice of the National Research Council (NRC) on water related "grand challenges" that could be addressed by the network and on the value of observatory networks in general. In response to the NSF's request, the NRC's Water Science and Technology Board (WSTB) assembled our committee of scientists and engineers with backgrounds in environmental engineering, economics, hydrology and hydrogeology, ecology, coastal and marine science, and computer science. The committee's statement of task (Box 1-1) was negotiated and agreed upon by the NSF and NRC. The timeframe for this study was short. The committee met only once but worked prior to and after that meeting to produce the consensus findings and recommendations stated in this report. Because the CLEANER program is in the early stages of development and the science plan was still being drafted during the committee's deliberations, the committee could not conduct a detailed review of this plan.

This report contains a summary, four chapters, and two appendices. Chapter 2 comments on the overall value of the observatory approach. Chapter 3 identifies and describes several "grand challenges" and particular water research questions that the CLEANER program might address. Chapter 4 discusses aspects of the program implementation, including sustainability issues, coordination and integration with existing programs and other observatory networks, the network's infrastructure, and opportunities for dissemination, education, and outreach.

BOX 1-1
Statement of Task

A committee formed by the Water Science and Technology Board (WSTB) will advise the National Science Foundation on its Collaborative Large-Scale Engineering Analysis Network for Environmental Research (CLEANER) initiative with respect to (1) the science plan and (2) the potential usefulness of the program. Regarding the science plan, the WSTB will identify some (5-6) of the major issues in the area of water quality and water resources that present "grand challenges" and that lend themselves to being addressed by CLEANER, i.e., perhaps providing the targets for observation and modeling efforts. Regarding the second issue, the WSTB will comment on the overall value to engineering and other potentially interested disciplines of networked environmental observatory facilities to improve our understanding of complicated, large-scale water quality and water resources problems and the development of cost-effective engineering approaches to their solution. The scope of issues to be considered by the WSTB will be limited to water quality and water resources; i.e., air will only be considered to the extent that it affects water. Note that for purposes of this study, a "grand challenge" is defined to mean a major scientific and/or technological task that is compelling for both intellectual and practical reasons, that offers potential major breakthroughs on the basis of recent developments in science and technology, and that is likely to be feasible given current capabilities and a serious infusion of resources.

2
CLEANER and the Observatory Approach

The National Science Foundation's (NSF) mission is to support the advancement of fundamental science and activities that transform the science and engineering disciplines to meet future needs. The NSF programs are continually challenged to support efforts that will enhance understanding of the sciences and engineering, resulting in improvements that are both incremental and transformative. Furthermore, NSF programs expand fundamental knowledge and support the application of that knowledge for the betterment of society. A growing challenge is the advancement of programs that address disciplinary issues of scale, both in time and in space, particularly when a discipline could be transformed by multidisciplinary and interdisciplinary efforts.

The environmental observatory program can be a key and unique contributor to the future development and transformations of environmental engineering and science. An observatory that is successful in this transformation will likely have several fundamental characteristics. First, it should provide the focus for the development of new measurement technologies, allowing for the expansion, and integration of measurements over different scales of space and time. Second, the observatory should establish a constancy of measurement and support a robust data environment. These data and analyses tools should facilitate the identification of basic processes, the development of new theory and new modeling and forecasting capabilities, and support adaptive management decision-making. Finally, the observatory should serve as a center of excellence in measurement, data analyses, and simulation. It should serve as a catalyst for the evolutionary development of measurement capability, and for the transformation of environmental science and its relationship with other sciences.

The scientific goal and strategic intent of the Collaborative Large-scale Engineering Analysis Network for Environmental Research (CLEANER; or if combined with the Hydrologic Observatories of the Consortium of Universities for the Advancement of Hydrologic Science, Incorporated (CUAHSI), WATERS [see note in Chapter 1]) is to improve our understanding of the Earth's hydrologic and associated biogeochemical cycles across spatial and temporal scales—enabling quantitative forecasts of critical environmental processes, especially those in human-stressed areas (e.g., urban). It is also a CLEANER goal to develop innovative scientific and engineering tools that will enable the development of more effective adaptive approaches for resource management and creative solutions to environmental problems. The committee evaluated the information provided regarding the CLEANER observatory approach and reached conclusions regarding its value and overall benefits, its transformational potential, and its ability to fill key information gaps.

VALUE OF THE OBSERVATORY APPROACH

The justification for a CLEANER environmental observatory network derives from our current inability to fully understand large-scale environmental processes and thereby develop new and more effective management strategies. First, we lack the infrastructure to collect basic data at the needed temporal and spatial scales and resolution. Second, even with such data, we lack the means to analyze, integrate, and synthesize data across scales from different media and sources (e.g., observations, experiments, model simulations). Third, because of insufficient basic data we lack an adequate understanding of many underlying processes. This makes it difficult to build sufficiently accurate models and decision support systems for predicting the effects of different management strategies on society and the environment.

Presently there exists a variety of environmental observations and surveillance programs (see Chapter 4). Examples of such observation networks include those of the U.S. Geological Survey (hydrology and water quality at selected sites under the National Water Quality Assessment (NAWQA) program), the National Oceanic and Atmospheric Administration (weather), the U.S. Forest Service, the National Park Service, the Environmental Protection Agency (Regional Ecological Monitoring and Assessment Program), and existing programs of the NSF (e.g., the Long-Term Ecological Research (LTER) Network). All of these national observatories or monitoring programs provide valuable data, but few provide a fully integrated measurement and data analysis effort designed to advance and transform a discipline in a setting that will allow rapid interdisciplinary dissemination of fundamental and comprehensive data.

Significant advances in our knowledge of water quality processes have been achieved in the past on relatively small scales. Groundwater quality observatories were common in the 1980s, such as the Borden Landfill Site in Ontario, Canada, and the Traverse City Coast Guard Site in Michigan. These are examples of successful observatories where multidisciplinary teams advanced our understanding of hazardous waste remediation and natural attenuation. Such observatories were critical in the development of numerous environmental sciences including contaminant hydrogeology, environmental microbiology, biogeochemistry, and risk assessment. They illustrate the potential important benefits derived from observatories that consider the quality as well as the quantity of surface waters together with changing land uses, pollutant loadings, and other human-induced activities in urban systems over larger spatial and temporal scales. Such multidisciplinary observatories are particularly timely considering the increasing complexity and multi-media nature of water-related environmental issues and challenges.

Based on experiences with other observatories, including land-focused, large-scale LTER projects and other smaller scale water quality efforts, there is every reason to believe that the larger scale CLEANER environmental observatories should:

- provide environmental data needed for developing the engineering and science required to address complex environmental problems;
- promote the integration of relevant multiple disciplines;
- provide a structure for sustained collaboration among the environmental engineering and sciences and social sciences to achieve disciplinary as well as multidisciplinary advancement, both in theory and in practice;
- ground the disciplines in information that is more complete, uniform, and transferable; and
- support the scientific and engineering teams needed to meet these grand environmental challenges.

CAN CLEANER BE TRANSFORMATIVE?

One respect in which the results of the CLEANER observatories can transform our thinking and knowledge is by better defining and establishing how ecosystem processes contribute to the human economy. CLEANER should contribute in critically important ways to the understanding of the influence of alternative regimes of water quality and quantity on ecosystem structure and function (e.g., productivity, biogeochemistry, biodiversity) and in turn, on engineering requirements and environmental decision-making. For example, stream ecosystems and associated floodplains are important in storing and releasing water during high and low flows, for nutrient retention (and thus for enhancing water quality), for wildlife habitat, for maintenance of biodiversity, and other ways. Furthermore, since many of the manifestations of global climate change and other global trends on human society will be felt through impacts on aquatic systems, CLEANER also should be helpful in detecting and determining the impacts of climate change on environmental and engineered systems as well as offering new engineering approaches in an altered environment.

Until the beginning of the industrial revolution, low-technology natural processes provided energy in support of the human economy. This energy was used directly as food, fiber, and fuel, and indirectly through such things as provision of clean water, topsoil formation, waste assimilation, and climate moderation. The rapid expansion of the use of fossil fuels over the past two centuries added a significant source of energy for the human economy and permitted exponential human population growth and energy use. Fossil energy use has both obscured the importance of more natural system energies and diminished them through human impact. There is growing evidence that availability and use of one of the most important fossil energy sources, oil, will soon peak globally and then decline. Even if this does not happen, it would seem that its price will continue to increase over time, likely at accelerating rates. If this is so, then energy from more natural ecosystems, (e.g., biofuels) will likely assume a relatively more important role in supporting the human economy. Therefore, programs such as CLEANER, that significantly contribute to our understanding of natural ecosystem processes and how to manage them in more sustainable ways, will be critically important. If successful, they should transform the way that society views natural systems.

A corollary transformative agenda is how an observatory program contributes to the many dimensions related to humans. Human activities affect the environment and are affected by the environment. Although impact analyses have been commonplace since the 1970s, seldom has a prediction been followed up by studies to determine if the prediction was correct. Further, human influences are now pervasive with effects monitored even in wilderness areas. Clearly, to address human dimensions it is necessary to study large-scale and long-duration phenomena. This is the main rationale of observatories.

The consideration of human dimensions also requires protection of human systems from adverse environmental change. Biophysical and social phenomena are closely interrelated. Understanding of processes and linkages among environmental characteristics and human systems is essential. Thus, the scientific issues addressed by CLEANER must include both the biophysical and social components. Without this understanding it is difficult to develop effective engineering approaches to managing these complex dynamic non-linear systems.

Social science data collection requires infrastructure. Some of this infrastructure is already in place. The U.S. Census, for example, has data of relevance to the science described here. However, the Census is by no means complete in terms of its description of the built or managed environment. Analyses of existing social data (including land cover, land use, and infrastructure data) are needed to identify the data gaps. Moreover, the data that do exist require *integration* with spatial biophysical information. The integration of social and biophysical data is a data infrastructure issue. For example, both social and physical data are collected increasingly by remote sensors linked to computer networks (e.g., satellite imaging, real-time traffic, usage monitoring). Biophysical data will come increasingly from sensors linked to cyberinfrastructure networks. This topic is further discussed in Chapter 4.

Additional examples of ways in which CLEANER can be transformative are presented in Chapter 3 where we review some research challenges that CLEANER could address.

HOW CAN CLEANER FILL IN THE GAPS?

Gaps remain in our understanding of the environment. Some of these gaps can be addressed by an observatory approach. One cannot observe ecosystem behavior on scales relevant to managers of large-scale environmental systems, such as river basins as large as the Mississippi, or ecosystems such as the Everglades, without taking measurements of processes and attributes at those spatial scales. Bringing part of those ecosystems into the laboratories helps researchers gain knowledge of individual components of particular processes, but not of the ecosystem as a whole. For example, how can human reaction to air and water quality be measured or quantified in a laboratory in isolation to the other influences on their behavior? How can one predict the fate and transport of pollutants in surface water and groundwater systems in the Everglades without measuring pollutant concentrations along with the water flows and volumes in those water bodies? Integration of laboratory and field-based investigations of the physical and socioeconomic sciences in the CLEANER program should fill major gaps in the environmental sciences.

We need to address fundamental gaps in our understanding of the environment and how humans interact with it. We need more and better quality data to evaluate the impact of human activities on environmental processes at multiple spatial and temporal scales, including the effects of urbanization and engineering systems and changes in types and amounts of pollutants associated with changes in land and water use. Data are also needed to establish a clearer etiology between water quality and the magnitudes of extreme events. We need to study global climate change within a hydrogeochemical context, including the propensity to propagate water-borne infectious diseases or hinder ecosystem functioning and biogeochemical cycling. These studies require data over large spatial and temporal scales. The availability of such data is a critical need if we are to validate conceptual and mathematical models and develop improved forecasting capabilities that are increasingly needed to enhance decision-making and environmental risk management.

Examples of forecasting capabilities that are of national interest and have impacts on water and other environmental resources include:

- the occurrence of red tides along our coastal zones;
- the dynamics of anoxia and hypoxia in the Gulf of Mexico and the Chesapeake Bay and their impacts on fisheries resources;
- the degradation of river systems such as the loss of wetlands and water quality deterioration in the Mississippi and other basins;
- *Cryptosporidium* and viral outbreaks in potable water distribution systems;
- the spread of water-borne pathogens requiring beach closings;
- drought conditions that increase the propensity for rangeland and forest fires;
- new environmental and public health impacts of emerging pollutants;

- developmental toxicity of aquatic species chronically exposed to low levels of xenobiotics;
- early warning systems for diminished value of ecosystem services;
- impacts of changes in our energy sources, supplies, and uses;
- impacts of growth and changes in our agricultural practices;
- very low frequency events such as floods and accidents that can cause major disruption to environmental and human systems;
- short-term events (e.g., storm water generation) where multiple factors interact to produce concentration/duration/frequency changes that are key to predicting consequences such as the extent and impact of non-point pollution; and
- long-term consequences of human-accelerated environmental change where effects are produced over time scales of generations and responses are typified by subtle changes in complex systems' characteristics.

SUMMARY

It is our conclusion that CLEANER's proposed environmental observatory network has the potential to accomplish a number of objectives. If implemented, it should provide over time extensive and essential information for the improved management of stressed environmental resources. From the integrated physical, chemical, biological, and socioeconomic data obtained from CLEANER's observatories, we should gain an improved understanding of how complex environmental systems function and interact with and are impacted by human activities. The data and understanding stemming from this observatory approach should allow for improved forecasting capabilities and understanding and lead to solutions to the impacts of urbanization and land and water use changes.

In addition, CLEANER should contribute to science and engineering education by engaging the academic community collaboratively in complex, large-scale, multi-disciplinary, real-world problems. As a note of caution, certain conditions need to prevail and pitfalls avoided for the full potential of CLEANER to be realized. These are discussed in Chapter 4.

3
Grand Water Challenges and Research Questions

In 1998, the National Science Foundation (NSF) asked the National Research Council (NRC) to identify the most important and challenging scientific questions across all environmental sciences. These were to be called the "grand challenges." In response, an NRC committee was formed and after two years of study published a report titled *Grand Challenges in Environmental Sciences* (NRC, 2001). These challenges were to improve our understanding of:

- biogeochemical cycles and how they may be impacted by human activities;
- biological diversity and ecosystem functioning and how they are impacted by human activities;
- climate variability, and how it is being altered by human activity;
- hydrologic forecasting to predict changes in surface water, groundwater, sediment, and interactions with land and aquatic ecosystems;
- infectious disease pathogens and their relationship with the environment, ecosystems, other pathogens, hosts/receptors, and their threats to other living organisms;
- institutional impacts on human use of environmental resources;
- land-use interactions with hydrology, ecology, and human welfare; and
- life cycle of materials used by humanity over space and time.

Our committee believes these "grand challenges" are as relevant today as they were when published, especially from a water science and technology perspective (the scope of our assignment). Each of these challenges can be better met, and perhaps some can be only met effectively, by the implementation of the proposed environmental observatories for hydrology, environmental sciences and engineering, and ecology.

In this chapter we identify some important and complex, water-related research issues and questions that stem from these grand challenges. Successfully addressing these issues and questions will depend largely on the availability of large-scale, comprehensive, and integrated physical, biological, chemical, and social data and information derived from these environmental observatories.

RESEARCH CRITERIA

The NSF has identified several research criteria for the types of questions the Collaborative Large-scale Engineering Analysis Network for Environmental Research (CLEANER) seeks to address. They are explained below. The committee believes these criteria can be used to set priorities not only for the research activities associated with the environmental observatories, but also for the design of the environmental observatories themselves, including data to be collected and the characteristics of the associated cyberinfrastructure networks. The research results supported by data collected through CLEANER could lead to substantial advances in the environmental sciences and have measurable, positive effects on the environment. CLEANER should strive to achieve this by:

- providing advanced sensor systems for data collection, advanced tools for data mining, aggregation, analysis, and visualization, and predictive modeling of environmental management strategies;
- identifying effective adaptive management approaches for human-stressed complex environmental systems based on enhanced site observations, experimentation, modeling, engineering analysis, and design;
- promoting and improving interactions among a broader group of engineering and science communities, including social scientists, in ways that result in greater benefits than would come from individual separate investigations; and
- engaging the academic and government scientists collaboratively in identifying, examining, and providing possible solutions to complex real-world problems.

These goals can serve as criteria for selecting the broad research questions to be addressed using the data and infrastructure provided by CLEANER. This chapter identifies some research areas illustrative of what should help achieve these goals.

RESEARCH AREAS

Research appropriate for inclusion in CLEANER can be divided into three main categories: (1) interactions among humans, the environment, and ecosystems; (2) innovative engineering approaches for improving water quantity and quality management; and (3) design of CLEANER's environmental observatories. The first two categories group research questions designed to advance knowledge of phenomena and processes and to provide tools and information for water management to sustain a healthy economy. The research questions in these two categories represent challenges in water environmental science and engineering. The third category includes research issues related to the design of CLEANER observatories and the development of tools and technology that will permit the collection of long-term data over large scales. These three broad research areas are obvious candidates for inclusion within the proposed CLEANER environmental observatory network program.

Interactions among Humans, the Environment, and Ecosystems

Research Question: How can we better understand biogeochemical cycling in river and estuarine systems? How are these cycles influenced by human activities?

Over the years, our nation's urban river/estuarine systems have been degraded by habitat/watershed alteration and by numerous stressors, including rural and urban point and non-point runoff, industrial waste discharges, combined sewer overflows, landfill leachate, atmospheric deposition, and invasive species. These stressors have altered the cycling of nutrients, in particular carbon, nitrogen, and phosphorus in terrestrial and aquatic systems. Although these perturbations to hydrologic systems are particularly noticeable in urban areas and in coastal areas close to population centers, they are observed in many other parts of the nation, even in more pristine environments.

Environmental observatory data should reveal how natural systems may be perturbed by humans and their activities. To this end, one strategy may be to develop similar observational/model-building programs focusing on a range from the more pristine to the more heavily impacted systems. A comprehensive network of sensors deployed in these increasingly impacted systems is likely to shed new light on physical, chemical, biological, and geological processes. This approach would likely have a high degree of success if the proposed environmental observatories provide data of sufficient temporal and spatial resolution to quantify the dominant environmental processes.

The development of continuous measurement technologies would provide a unique opportunity to understand processes controlling perturbed aquatic systems. As human population continues to increase, these ecosystems will likely be stressed further. Consequently, evolving patterns of water quality variability are anticipated. Historically, scientific studies have examined such variability primarily at weekly, seasonal, and annual time scales in recognition of complex biogeochemical interactions and their associated time scales. However, recent studies indicate that short-term (e.g., hourly) water quality variability can greatly increase our understanding of processes and can lead to strategies for mitigating adverse human impacts on the water quality and ecology of our nation's urban rivers and estuaries (Cloern et al., 1989; DiLorenzo et al., 2004). The observatory approach seems well suited to study such variability and develop associated physical and biogeochemical controls.

Research Question: To what extent can humans alter their environment and its ecosystems while still sustaining desired levels of ecosystem function? How far can humans alter water regimes and landscapes before recovery cannot be economically achieved?

Environmental and ecological systems, of which humans are an integral part, can be overwhelmed by human actions, thus compromising system services. Water quality managers use the term "assimilative capacity" to denote just how much of some pollutant can be discharged into a water body without violating some threshold condition, such as a water quality concentration standard, or the minimum conditions that will sustain aquatic life. The focus has been on modeling, predicting, and managing the pollutant assimilative capacity of water. CLEANER's proposed environmental observatories would provide the opportunity to address larger, more complex, and multi-component environmental systems. The focus and scope of management could be expanded from the typical point and non-point sources of pollutants and smaller scale activities to the consideration of system level issues in landscapes and ecosystems.

The importance of ecosystem services as a critical component of our human-dominated environment is well known (Palmer et al., 2004). The improved understanding that could be gained from research stemming from CLEANER would enhance our ability to better manage and protect those ecosystem services. Research undertaken using the data obtained from environmental observatory programs could identify just how far humans can stress ecosystems before catastrophic regime shifts produce a loss of services that cannot be economically engineered, restored, or replaced. Observatories where a range of differently stressed conditions exist and are monitored, and that are subjected to different management strategies, should provide the data and information needed to better understand the causes of such shifts in ecosystem states and services and how to prevent them. For example, the Everglades restoration project in south Florida is essentially an existing large-scale environmental observatory in which there is a range of environmental states and ecosystem conditions. Human activities have altered many of the Everglades water regimes and landscapes. The monitoring and study of this system over time gives the managers of that system useful information on how it works and how to better manage and restore it (NRC, 2003). Observatory networks in other regions of the country can help fill this information need in those regions.

Through observatory programs, there exists the potential for the development of modeling techniques that will offer more reliable long time period predictions, which will be adapted and validated over time as new data become available. These models, supported by observatory data, will continually refine our understanding of ecosystems by offering a feedback loop: environmental data are used to build and run models and model outputs are used to assess initial assumptions that drove data collection so that new data collection can further refine the models and improve prediction. This iterative process must respond and adapt to changing environmental/ecosystem and human factors. Further, we must recognize the critical social component and sustain a long-term commitment to data collection and model development needed to continue the research needed to support any proposed adaptive prediction and management strategy.

Research Question: How will changes in climate, land cover, and land use affect water quantity and quality regimes and how will that impact ecosystem health and other uses of water such as for drinking, irrigation, industry, and recreation?

Climate and land use are two of the most important factors influencing aquatic ecosystems. Both of these factors will continue to undergo change in the next half century or longer. Climate change is well documented, yet how it will affect ecosystem function over time is less certain. Land use change is known to affect stream response, yet the pathways of water and constituent transport are not well understood, especially in human-dominated landscapes (Allan, 2004). Environmental observatories should enable scientists and engineers to document hydrologic pathways and understand the consequences of differences in network structure for aquatic ecosystems.

Questions regarding land use change that alter landscapes and affect ecosystem function include: how much does strip mining affect water quality; what is the effect of paving in urban areas on ground water recharge; and how much of the nutrient load in an estuary is caused by poultry farming? Understanding how the nation's aquatic resources and their ability to provide ecosystem services will respond to changes in climate and land use is an important, but difficult research goal. An observatory approach offers the promise of providing answers to these and other questions that are difficult if not impossible to answer using more conventional research strategies.

The direct effects of climate and land use change on lakes, rivers, and wetlands, although the subject of many studies, are still difficult to predict across a range of local, regional, and continental scales. Because lakes, rivers, and wetlands provide many important ecosystem services, such as water for drinking, irrigation, industry, recreation, and waste treatment, natural and socioeconomic processes are intertwined in complex ways that must be taken into account. For example, as aquatic resources change in quality, humans respond in a variety of political, social, and economic ways to mitigate (or exacerbate) these changes. The reciprocal feedbacks inherent in coupled human and natural systems (humans affect ecosystems which then affect humans) makes understanding how climate and land use change will affect aquatic ecosystems even more complex and difficult.

Developing the needed understanding will require a series of activities including long-term observations, comparative studies, modeling, and experiments. Environmental observatory systems have the potential to inform and support all of these activities. Observatory system activities must include measurements and modeling of flows of water and solutes (including inputs, outputs, and transport and changes within the system), detailed observation and modeling of land use change at a variety of spatial scales, methods of making regional scale climate projections, and forecasting human responses to, and economic impacts of, changes in the quantities and qualities of aquatic resources. This better understanding should facilitate the development of forecasting tools to explore alternative future scenarios. These tools could be used to examine how aquatic ecosystems are affected by climate change and alternative engineering infrastructure designs, management policies, agricultural practices, and other environmental modifications under human control. A CLEANER network could focus on biogeochemical processes and contaminant fate and transport and interface with various biological investigations. The following are examples of the kinds of questions that could be addressed:

- How does the replacement of small streams with stormwater pipes or tile drains (or the loss of small streams because of groundwater pumping) alter the amount of nitrogen (or other elements or contaminants of interest) exported from a watershed?
- Is there a threshold of network alteration after which the behavior of the system is fundamentally different?
- How can strategically restoring a wetland in the landscape affect processes?
- Can network analysis contribute new insights or approaches that would lead to a better understanding of the movement of water, elements, and organisms in natural and human designed stream networks?

Innovative Engineering Approaches for Improving Water Quantity and Quality Management

Research Question: How can we improve hydrologic forecasting?

An intelligent environmental control system (IECS) could be developed that would incorporate comprehensive hydrologic data into the design and operation of complex water resources systems. An IECS would allow for water flow and water quality monitoring of an urban ecosystem and would help control the use of resources to enhance and protect ecosystem function and human health. This system could include:

1. a network of sensors to measure flow;

2. robotic water quality monitoring sites deployed in the watershed of an urban ecosystem;

3. near real-time analysis capability that uses the sensor data with sophisticated "whole-system" models to forecast conditions;

4. a robust communication system linking sensors and automated models with "control sites;" and

5. control sites where environmental managers and/or automatic control devices could act on the forecast and make modifications to preserve the quality of resources such as water supplies and receiving waters.

Local, state, and federal agencies, including the National Weather Service, National Oceanic and Atmospheric Administration, and U.S. Geological Survey, have made investments in providing information for forecasting. Partnerships with these agencies can provide systems that can be used by water resource planners and/or managers to evaluate and make decisions on the use of alternate water supplies, alternative levels of drinking or wastewater treatment, or alternative locations of effluent discharge. For example, during a drought, surface water sensors and water quality models might indicate that dissolved oxygen will decrease to unacceptable levels prompting wastewater treatment plant operators to decrease nutrient discharge to receiving water. If the "control loop" extends to long-term policy-level decisions or near real-time actuation of a sluice gate/valve, such an IECS could significantly enhance the protection and use of urban ecosystems and the health and safety of its human inhabitants.

Assessing ecosystem condition, modeling, and process-level studies are critical components in programs of environmental research and management. Assessing ecosystem condition establishes linkages to human and ecosystem health, provides insight into watershed processes, supports development, testing, and application of mathematical models, assesses efficacy of environmental management and control efforts, and provides a vehicle to educate students and engage the public in important local environmental issues. Mathematical models are effective integrators of assessment data and related research activities, including the results of process studies. They provide a quantitative vehicle to test the understanding of complex ecosystems. Further, successfully verified models provide the foundation to evaluate management alternatives and guide rehabilitation of impacted ecosystems. Process- level studies provide a basic understanding of phenomena and, when conducted quantitatively, can be used in process model formulation and parameterization. Assessment, modeling, and process-level studies should result in improved ecosystem management.

While prototypes of the IECS have been developed, there are several barriers to a fully functioning, integrated system that need to be overcome. These barriers include the development of sensors for several critical water parameters (e.g., nutrients, toxic contaminants); the development, testing, and application of predictive water quality models and the integration of these models with the near real-time data acquisition system; process-level studies and field experiments to provide a quantitative understanding of critical processes, and to parameterize and test models; and the timely transfer, processing, and management of streams of environmental quality data. We now lack sensor technology to assess anything more than rudimentary biological processes and phenomena. It may be possible to use specific photosynthetic pigments to characterize algal assemblages and detect potentially harmful algae, but what about vertebrates and invertebrates? And having real-time knowledge of where fish are swimming in a river system could be extremely valuable in making decisions on modifications to dam infrastructure, reservoir water releases, water diversions, and wastewater effluent discharges during critical periods.

Research Question: How can we find solutions to existing and emerging problems involving contaminants in the environment that affect ecosystems and human health?

A number of issues have emerged that involve the fate and transport of contaminants and are of national concern. Some of these issues are in need of innovative engineering research based on data that could be obtained from the observatories. We need research results that can assist managers in dealing with contaminated sediments and contaminants such as pharmaceuticals and household products affecting ecosystems and human health.

Containing or removing contaminated sediments is one of the most difficult site environmental remediation issues managers face today. Management actions typically are designed to reduce or eliminate the risk of contaminated sediments to humans and the environment. Contaminated sediments in water bodies are typically subject to temporally and spatially varying overlying flows. Under extreme high flows, often resulting from storm events, these contaminated sediments can be suspended and transported to new sites. The volumes of these contaminated sediments can exceed, in some cases, millions of cubic meters. This creates challenges not only when considering their removal but also their disposal on landfill sites. In addition, the removal of contaminants from the sediments typically results in the contamination of even more water. All of these problems make remediation of contaminated sediments a difficult and costly process. Effective low-cost management of contaminated sediments is rarely possible. Research is needed on management options that do not require removing the contaminated sediments. An environmental observatory in a location such as the Great Lakes or similar setting would provide the opportunity to monitor and study impacts of sediment management measures on the aquatic environment.

Residuals from pharmaceutical and personal care products are entering the aquatic environment. Their long-term impacts on natural ecosystems or on human health are not known. A challenge for observatories is to determine what products are the most deleterious for long-term ecosystem health and to develop sensors to measure them at relevant and temporal scales. Investigations using molecular analytical techniques might provide additional information about cellular changes that affect bacteria and algae within an ecosystem. Several new methods exist that need further development and application to examine the effects of contaminants, such as pharmaceuticals, on ecosystem health. Near real-time monitoring of water microbes could be realized to determine population mutations and information about community structure level (e.g., population shifts, changes in diversity, and tolerance to stress).

Design of CLEANER's Environmental Observatories

Three overarching design features incorporated into the research questions will distinguish the CLEANER environmental observatories from other programs. These design features of CLEANER's environmental observatories should:

1. include multiple types of sensors for collecting comprehensive and integrated environmental data over large spatial and long temporal scales;
2. include a robust and adaptable cyberinfrastructure that can link to other databases; and
3. permit the collection and use of social science data along with physical, chemical, and biological data needed to address environmental problems caused by human activities.

Use of Sensors

The development and implementation of various types of remote and *in-situ* sensors and their data transmission networks is an important and prominent component of CLEANER and other environmental observatories. For many chemical and biological parameters we would like to measure, we are sensor limited. A report entitled *Sensors for Environmental Observatories* (NSF, 2005) from a NSF-sponsored workshop in December 2004, points out the need for:

- new types of sensors with new capabilities;
- the ability to link sensors to a broader cyberinfrastructure network; and
- long-term autonomous deployment and maintenance.

Physical sensors, such as for the measurement of heat, are the most developed, whereas chemical and biological sensors are the least developed. Networks of embedded sensors are emerging that allow for integrated, intelligent, self-regulating, and self-correcting systems. New sensor technologies include nanosensors that are embedded within plants and animals as well as in water supply pipes, treatment plants, and reservoirs and wastewater collection and treatment systems. This technology also includes computational tools for data mining, sensor calibration, and verification. Working with the federal agencies, near real-time monitoring with such sensor and associated technology with ties to weather data, satellite information, etc., can improve the accuracy and breadth of models used for predictions and reduce response times to natural or human-caused adverse environmental events.

Integrated Data Collection and Storage

The individual environmental observatories under CLEANER should be problem-oriented and hence focus on data collection relevant to current and possible future problems. As problems change, scientists and engineers face a major challenge in predicting what data should be collected today that will meet the data needs of researchers and managers in the future. For example, data collected to provide regular surveillance of condition and state indicators might fail to meet future needs for problem analysis. For example, the widespread occurrence of antibiotics in freshwaters was not anticipated or monitored until fairly recently, and we are not currently monitoring nanoparticples in the environment. Surveillance programs may be based on parameters and frequency of sampling that can provide time correlation, but little insight into process. Thus we have snapshots of condition or state with little correlation to mechanisms, causes, or possible outcomes. As scientific knowledge increases, an evaluation of the adequacy of the surveillance program needs to be addressed. In a quality assurance plan, the starting point for a data collection effort is the identification of the program and project objectives. Objective statements drive both the data collection and analysis efforts. Quality control is an important issue for large databases if the data are to be compared.

A challenge is how to control and record data quality collected from the field by different methods and analyzed by different laboratories and by the use of different types of sensors. The challenge in design of an observatory network will be adopting methods to assure that problem solutions are not just local and that the maximum utility is achieved from any surveillance data. The observatories should not just make measurements; the observatories should use measurements to identify principles and processes that are transferable to other locations.

The need exists for the development of a system to house and share the data obtained from the observatories. A robust cyberinfrastructure that provides a common framework and can link to multiple databases will facilitate a national resource for hydrologic, environmental, and social data. The cyberinfrastructure issues related to storage, access to, and sharing of data from the observatories are discussed in more detail in Chapter 4.

Integration of the Social Sciences

Each of the NSF planned environmental observatories calls for the integration of social science data and research along with the hydrologic, environmental, and ecological research programs. This is absolutely necessary if human interactions with the environment are to be better understood. How can this integration best be done? Harnessing the value that social science can bring will require reaching out to involve and fund the social science community and to help NSF articulate why social sciences are a vital part of the observatory mission.

While all environmental observatory plans call for the integration of the social sciences and biophysical sciences and data measurement and collection capabilities, this may not happen unless NSF adequately funds such activities. Although the origins of the proposed environmental observatories came from physical sciences and engineering, this makes the need for a strong social science component no less important. The primary reason research in the natural sciences and in engineering is funded is to improve the welfare of society. But how society values and uses the advances in the natural sciences and engineering is a social science research issue. Research in the "policy relevance" of the observatory programs is vital to their initiation and continuation over the long term, and to further understanding the dynamics between humans and the state of their environment.

Watersheds are not pristine, closed systems. Accordingly, analyses of the fate, transport, restoration, preservation, and human impact of environmental resources depend on intervening social variables. Many environmental systems are highly engineered. This engineering may be formal (e.g., the U.S. Army Corps of Engineers operating a reservoir system or the stormwater infrastructure of a city) or informal (e.g., pollutant deposition arising from various human activities). Cause and effect in the biophysical system cannot be satisfactorily demonstrated unless these social variables are part of measurement and modeling. Moreover, ecological and social interactions work both ways. Ecological conditions can foster economic activity (natural amenities lead to employment and development), which can in turn lead to ecological degradation. Social scientists are interested in the human affects of and responses to these decisions and interactions. And the results of social science research should feed back into the biophysically predictive models, because human activity affects biophysical outcomes.

Determining the value of information is a social science issue. Social science helps explain how the value of information is measured or predicted. Social science can help relate biophysical change to its impact on human communities. And social science may provide partners more adept at public communication. Without participation of the social sciences, the biophysical and environmental engineering focus of the observatories may be missing opportunities to demonstrate their broader value. Finally, the observatory-based CLEANER programs need to educate social scientists. The social science community has a limited understanding of what these programs are and their future potential for the social as well as physical sciences. Harnessing the value that social science can provide will bring added public (and political) support but will require significant outreach to the social science community.

SUMMARY

This chapter identifies some of the major challenges that could be addressed by those involved in the planning, design, and operation or use of a CLEANER environmental observatory network. Having a long-term large-scale integrated data base obtained from environmental observatories should make it much more likely that research directed at the challenges similar to the ones we pose will begin to provide knowledge and will lead to more effective engineering and management actions that improve, protect, and sustain our environmental resources and ecosystems into an uncertain future.

Regarding the interactions among humans, the aquatic environment, and ecosystems, a CLEANER network of observatories could undertake research to:

- better understand biogeochemical cycling in river and estuarine systems and how these cycles are influenced by human activities;
- understand the extent to which humans can alter their environment and its ecosystems while still sustaining desired levels of ecosystem function and determine how far humans can alter water regimes and landscapes before recovery cannot be economically achieved; and
- learn how changes in climate, land cover, and land use affect water quantity and quality regimes and how those changes will impact ecosystem health and other uses of water such as for drinking, irrigation, industry, and recreation.

Regarding an increased understanding and improved management of our biophysical environment, a CLEANER network of observatories could undertake research to:

- improve our capabilities in hydrologic forecasting and
- find solutions to existing and emerging problems involving contaminants in the environment that affect ecosystems and human health.

There are also research challenges associated with the design and operation of CLEANER's environmental observatories. These include issues related to:

- the use, deployment, and evaluation of multiple types of sensors for collecting comprehensive and integrated environmental data over large spatial and long temporal scales;
- the development of the components of a robust and adaptable cyberinfrastructure that can link to other databases; and
- the collection and use of social science data along with physical, chemical, and biological data needed to address environmental problems caused by human activities.

4
Implementing Environmental Observatories

The need for better understanding and management of the nation's environmental resources over past decades has led to the establishment of several federal, regional, state, and local monitoring and assessment programs. The National Oceanic and Atmospheric Administration's (NOAA) weather and ocean/Great Lakes monitoring, the U.S. Geological Survey's (USGS) national hydrologic monitoring and water quality assessment programs, the U.S. Department of Agriculture (USDA) Forest Service (FS) and Agricultural Research Service (ARS) experimental watershed facilities, and the Environmental Protection Agency's (EPA) Clean Air and Clean Water Act monitoring are examples of federal activities with practical or regulatory drivers. These programs, along with regional, state, and local monitoring and assessment activities, provide data useful to many fields of science and engineering, and contribute to the understanding of complex environmental phenomena.

These monitoring and assessment activities provide valuable information to research communities and management agencies. However, there remains a critical need for more integrated and comprehensive approaches to understanding and analyzing environmental processes that ultimately will help us better manage and improve the quality of air, land, and water resources. This need has motivated the planning of environmental observatory and research networks by the National Science Foundation (NSF). These initiatives are at different stages of planning and implementation and in many respects have been developed by separate scientific constituencies and separate directorates within the NSF. No single environmental observatory initiative as currently formulated will be sufficient to provide the integrated data sets, models, and predictive capability necessary to adequately understand and guide effective management of our nation's environmental resources in a setting where large scale, even global factors, must be considered. As a coordinated group, however, they might be.

Planning has been underway for the National Ecological Observatory Network (NEON) after several NSF workshops in 2000 addressed the needs for long-term ecological observatories. NEON will focus on large scale and interdisciplinary analysis of ecological systems (NRC, 2004a). The Ocean Observatory Initiative (OOI) is another NSF environmental observatory system at approximately the same stage of development as NEON; it is being designed to help better characterize processes occurring in the ocean. The Geosciences Network (GEON) grew from a series of workshops in 1999 and seeks to advance the field of geoinformatics in support of the geosciences. A national hydrologic observatory network that proposes to address atmosphere, subsurface, and surface dynamics of water movement is in the beginning stages under the leadership of the Consortium of Universities for the Advancement of Hydrologic Science, Incorporated (CUAHSI). NSF's Office of Polar Programs is also working to design a land/atmosphere/ocean-based Arctic Observing

Network that would collect, check, organize, and distribute arctic observations. Finally, CLEANER is a proposed network through which problems involving large-scale complex engineered systems and human-stressed environments would be addressed. As noted earlier, during the course of this study, the NSF was considering and planning for the merger of the CUAHSI Hydrologic Observatories and CLEANER.

These national environmental observatories are now being planned, each with a somewhat different focus area and each designed to meet somewhat different goals. Yet each observatory has a core focus on transformative developments in the environmental sciences. Because of the differences in the stages of development, these observatory programs will be ready for implementation at various times over the coming years. Even so, it makes sense to think about their coordination to take advantage of existing expertise, experience, and technology, and to avoid duplication of expensive infrastructure, including cyberinfrastructure.

COORDINATION OF ENVIRONMENTAL OBSERVATORIES

Coordination of Environmental Observatories within NSF

Because these individual NSF initiatives have been developed somewhat independently, there is danger of unnecessary and inefficient redundancy in developing data collection standards and infrastructure and in performing various research and associated activities. To effectively observe complex environmental systems and inform their management, a coordinated, administratively integrated effort will be necessary. Indeed, there is a danger that lack of coordination among different observatory designs will make the sharing of data, information technology, and education and outreach activities more difficult if not impossible across programs.

As these observatory initiatives develop, communication and close coordination among the programs are essential. It is apparent that the various environmental observatory projects currently in the planning process at the NSF have some similar basic components and needs. These needs include the development of a cyberinfrastructure, coordinated educational activities and outreach, and the co-location of some observatory elements to achieve needed data integration at lower costs. It makes scientific and economic sense to share infrastructure/capital that will meet common needs.

The scientific challenges to be addressed by each of the initiatives clearly require an integrated effort across the relevant disciplines (i.e., engineering, ecology, hydrology, earth sciences). For instance, the exchange of materials between terrestrial and aquatic ecosystems should be of interest to both NEON and CLEANER, which further suggests coordination with existing agency-based observatories and environmental assessment programs.

The NSF appears to recognize these issues and ongoing efforts to coordinate the observatory initiatives are currently underway. The NSF program officers leading the development of these initiatives have issued joint calls for proposals in the areas of sensor development and cyberinfrastructure that will benefit each of the observatory initiatives. Even more coordination and possibly joint management of these initiatives may be desirable as the programs reach implementation.

Serious consideration should be given to placing the various NSF environmental observatory programs under a parent organization that could be termed something like the "Environmental Observatory Networks" or EON. This parent entity would be responsible for cyberinfrastructure development, educational activities, outreach, and other shared activities across the observatory programs. This entity would facilitate collaboration and coordination among programs and minimize redundancy, while not impeding the progress of individual observatory initiatives. It would also help ensure that the observatory networks are well integrated spatially and across relevant landscape units. An independent expert committee outside of the NSF could provide advice and oversight on the research and support activities of EON. Again, this integration of observatories would contribute to data integration and reduce infrastructure redundancy and associated costs.

Coordination of Observatories with Other Agencies and Stakeholders

Many federal and state agencies have programs that support water resources research, monitoring, and management through in-house capabilities or by the distribution of grants. Federal organizations having significant water resources research programs include the NSF, USGS, U.S. Fish and Wildlife Service, USDA, EPA, Department of Defense, Bureau of Reclamation, Department of Energy, National Aeronautics and Space Administration, and NOAA (NRC, 2004b). The proposed NSF observatories will need to document their value in the context of existing state, regional, and federal programs that conduct similar types of investigations. Observatories should focus on filling scientific and engineering gaps identified by researchers at universities and managers of programs administered by the government agencies. The new observatory infrastructure needs to be designed to enhance existing infrastructure, if such infrastructure exists, without significant duplication. Expertise in the federal, regional, and state agencies on conducting watershed-based field studies, modeling, analyzing geospatial information, making ecological assessments, working with sensors, addressing water quality issues such as nutrients, toxics, pathogens and invasive species, and managing databases should be of value to investigations at CLEANER observatories. Close cooperation should result in mutual benefits and cost-savings.

Cooperation with federal, regional, and state agencies needs to be established at several levels that include: (1) coordination of data collection, (2) management of data, (3) sharing of techniques such as modeling capabilities and analytical methods, and (4) coordination of activities at sites where there are common interests between an agency program and a CLEANER observatory. The two major national water databases are the National Water Information System (NWIS; managed by the USGS) and STORET (short for storage and retrieval; managed by EPA). Both databases are available on the Internet, although they are not now compatible through one portal. Recent work funded through CUAHSI for its Hydrologic Information System (HIS) has advanced the development of a common portal to access water databases from different agencies. If ultimately successful, it will be a major achievement for the retrieval of water resource information. The NSF has proposed to have the data generated through all NSF-funded observatories available through a cyberinfrastructure.

Field-focused activities that are most likely to have common interests with sites selected for investigation by CLEANER are those managed by the USGS, the USDA ARS and FS, EPA, and the NSF Long-Term Ecological Research (LTER) programs. The USGS has several field-based programs, including the National Water Quality Assessment (NAWQA) program that focuses on watersheds and major aquifers to assess the status of, trends in, and causes of changes to the quality of the nation's groundwater and surface waters; the Toxic Substances Hydrology Program, through which long-term research is conducted at sites that represent different types of contamination, and a long-term small watershed program (Water, Energy, and Biogeochemical Budgets (WEBB) Program) at five sites, which focuses on processes in different climate regimes. The USDA supports watershed research through the ARS, FS, and Natural Resource Conservation Service. The ARS watershed network is a nested, multi-scale network designed to assess the hydrologic impacts of watershed conservation and management practices. The USDA FS supports experimental forest and range research sites. Nine of these sites focus on watershed research. The NSF LTER Network is designed to address long-term research to understand ecological phenomena that occur over long temporal and broad spatial scales. The LTER Network involves long-term ecological measurements and experiments at 26 sites in the United States and Antarctica, some of which are in human-stressed environments. The EPA conducts water-related research in its Office of Water and Office of Research and Development. EPA's Regional Environmental Monitoring Assessment Program (REMAP) is a research initiative aimed at helping to monitor and assess the status and trends of national ecological resources, including water quality. Also the EPA supports site-specific investigations such as in the Chesapeake Bay and Great Lakes. CLEANER is different from most of these other programs because it offers a large-scale focus on human-stressed environmental-hydrologic systems from the engineering perspective of identifying and evaluating innovative approaches to the solution of environmental problems.

There is also a need to coordinate with non-governmental organizations that are actively involved in addressing environmental issues in many areas of the country. In many major river basins, a variety of non-governmental organizations (i.e., the Nature Conservancy, the Wetlands Initiative, Environmental Defense) are working with various stakeholders to develop solutions to problems in the basins. The observatory networks should coordinate with these efforts to facilitate the transfer of applicable observations and analysis to address relevant problems.

Mechanisms to Achieve Coordination and Cooperation

Several measures can be implemented to help achieve successful coordination of the new observatories with existing federal, regional, and state programs. Activities that can facilitate coordination include: (1) workshops on specific topics, (2) information requests in proposals about existing infrastructure funded at the federal, regional, and state levels, (3) establishment of agreements with federal, regional, and state agencies, and (4) dialog in committees that have representatives from government agencies.

Workshops on specific topics can enhance scientific exchange and encourage coordination and collaboration. Workshops where parties, including university and government scientists and managers, work together to find solutions and identify directions are often more effective in establishing communication than are briefings that tend to become "show and tell" exchanges. The most successful collaboration is often achieved at the scientist-to-scientist level. Workshops should be designed to encourage this type of interactive exchange. By encouraging participation of others, the observatory networks can benefit by sharing costs and avoiding duplication of efforts.

Another measure to encourage collaboration with federal, regional, and state agencies is to require in the planning process that the existing infrastructure at a potential site be identified and that the agency supporting the infrastructure be notified and their goals documented. A solicitation of letters of support from the appropriate agency managers or scientists can be encouraged. This process is currently in place in several NSF programs.

Collaborative agreements between the observatories and government agencies will provide mechanisms for sharing resources. For example, the USGS and CUAHSI have an agreement, as of 2006, in regard to the USGS Hydrologic Instrumentation Facility (HIF) that covers the rental of equipment, such as that used for gauging streams. The agreement will save the observatories from having to purchase all their instrumentation and develop facilities to test, repair, calibrate, and house it. The instrumentation is located at the HIF and is used by the USGS for its investigations and thus is cost neutral to the USGS.

One approach to establishing cooperation with the federal agencies that have water resource research programs may be for the EON coordinator to interact with the Subcommittee on Water Availability and Quality (SWAQ) that was formed by the Office of Science and Technology, Executive Office of the

President. The SWAQ, created in 2003 initially for five years, has a membership of 18 federal agencies to "advise and assist the Committee on Environment and Natural Resources and National Science and Technology Council on policies, procedures, plans, issues, scientific developments, and research needs related to the availability and quality of water resources of the United States" (SWAQ, 2004). Although the future of SWAQ is uncertain, the NSF is a member of the subcommittee, and it is an appropriate group with which to exchange information and establish coordination.

CLEANER CYBERINFRASTRUCTURE ISSUES

National-scale environmental observing initiatives will need to coordinate and share resources to provide quality data products for accurate scientific analysis and forecasting. The scale of the scientific enterprise and the fact that there are numerous participating communities, agencies, and programs precludes a single home-grown bottom-up approach to observing system development and operations. Operating across distinct jurisdictional boundaries, with disparate policies and technologies, raises a number of challenges—both in infrastructure and operations. By considering these challenges during the planning of cyberinfrastructure initiatives associated with the environmental observatories, there may be some hope of achieving a high-level of system compatibility and integration that will benefit both the quality of the science and the economics of system development and operation.

Cyberinfrastructure for environmental observing systems includes hardware (i.e., sensors, actuators, networks, computers, storage platforms), software (i.e., middleware that supports different application components, tools, applications), and the standards and policies necessary for operations. Given the extreme heterogeneity of the technology base, the role of cyberinfrastructure in facilitating system integration will be paramount. A robust cyberinfrastructure can provide common frameworks, components, modules, and interface models that can be used in multiple observatories or applications.

There are several cyberinfrastructure activities underway that address aspects of the resource integration challenge. For example, CUASHI has initiated a Hydrologic Information System (HIS) project to integrate access to national water resources data, and there are plans to leverage this cyberinfrastructure for NEON. Extending this activity to include CLEANER, as seems likely given the merger of CLEANER and CUAHSI's Hydrologic Observatories, is one example of the types of cross-organizational collaborations that would facilitate the vision of an integrated EON.

In the following sections a few of the key issues are discussed related to creating a common cyberinfrastructure for environmental observatories: (1) policies—rules and guidelines for operations, (2) standards for data, networks, and instruments, and (3) the hardware and software of the cyberinfrastructure. A comprehensive approach to building an efficient and secure, scalable and extensible, environmental observing system will require careful design across all three areas.

Policies

Many of the challenging issues involved in integrating observing system resources center on governance policies. Who owns the resources (including data and physical resources—sensors, instruments, computing platforms, etc.)? Who can use the resources and under what conditions (including access control, resource contention and scheduling, intellectual property rights, publication, and citations)? Often these policies vary by community or project (e.g., requirements for timely public access to data products). Privacy policies and public disclosure of sensitive data (e.g., wetlands designations) also factor into information sharing activities and applications across observing systems and communities. The current practice in negotiating cross-agency (or cross-project) resource-sharing policies is typically limited in scope and heavily influenced by a small number of participants. A more comprehensive approach would benefit multiple observing system initiatives or the multiple users of a common environmental observatory network. Policies will be needed regarding the access and use of a variety of resources beyond data products, including the field-deployed observing system sensors and instruments, and the data center resources for data management, modeling, and analysis. A services-oriented architecture (see below) provides the engineering framework for building distributed resource-sharing applications; however, it is the policy specifications that will determine the efficiency and usability of such applications.

Standards

Standards with respect to observatory hardware, software, and research activities, including data collection, documentation, and storage, can facilitate cross-program applications. Standards can also constrain scientists and engineers, especially in an environment of rapid changes in technology. The challenge is to develop standards that can both facilitate multi-disciplinary activities and be adaptable to changing technologies and needs. Especially important are standards for providing metadata descriptors for key resources and infrastructure components.

Metadata perform a number of roles in observatory network design and operation, including facilitating application integration and locating, evaluating and using data products, sensors, communication and computer networks, software applications, and the like. For example the ocean observing community's Marine Metadata Initiative[1] and the CUAHSI HIS metadata

[1] *http://marinemetadata.org/.*

initiative have direct relevance to the CLEANER program. A common set of metadata specifications and tools would facilitate cross-observatory activities.

Most of the observing system standards to date have focused on data collection and products. Similar standards need to be specified for other resources including sensors, instruments, and actuators. The ocean observing initiatives (e.g., the Laboratory for the Ocean Observatory Knowledge Integration Grid [LOOKING][2]) have been exploring these issues, drawing on evolving standards.

Tools and Applications

Observing system cyberinfrastructure must provide the tools to implement polices and deliver services. The cyberinfrastructure goals include:

1. Interoperability—the ability to build applications across domains;
2. Extensibility—the ability to add new devices, components, tools, and applications; and
3. Scalability—the ability to add new computational resources to handle increasing demands.

These goals can be accomplished by developing: (1) an open architecture based on well-defined standards, (2) a common framework for application development and integration, and (3) an integrated suite of tools for resource discovery, access, and use. The requirement for an open architecture derives from the fact that there are numerous heterogeneous infrastructure components that are needed to satisfy the overall scientific mission. It is not reasonable to presume (or mandate) a particular technology product (e.g., database, geographic information systems (GIS), workflow package, analysis toolbox). In addition, observation system resources come with differences in protocols and performance. For example, there exists a large variety of sensor hardware platforms and software elements (i.e., operating systems, networking protocols, data base systems). Commercial off-the-shelf (COTS) sensors are equipped with transducers for measuring variables ranging from pressure, temperature, humidity, and light, to various complex environmental phenomena (e.g., dissolved oxygen, nutrient concentrations, current profiles). In addition, new generations of biological sensors are being designed and developed. The processing power of available COTS sensors ranges from 4 MHz to 400 MHz. Their radio bandwidth varies from few kilobits/sec to several Megabytes/sec. Typical operating systems available include TinyOS, MOS, Linux, and

[2] *www.lookingtosea.org.*

Windows CE. There are similar differences in the data center components and computer programming applications (e.g., NET vs. Java web service stacks).

Accommodating these heterogeneous components (including legacy resources and researcher/developer preferences [e.g., favorite tools]) dictate an extensible architecture. A commitment to an open architecture is not a commitment to open-source software products. Rather, it is an open set of standards and protocols that specify the functional interfaces to various devices, products, and services.

Data Availability and Sharing

This committee also recommends the selection of an open source standard for data collection, storage, and sharing. There are two major advantages. First, the data standard would support data sharing and analysis opportunities between CLEANER locations. The more consistent the data protocols, the more effectively the data can be shared among multiple CLEANER stations to examine common trends and responses. Second, definition of an open standard can more effectively expand the influence of the CLEANER program. Not all data will be collected by the CLEANER program lead. Historic data bases might need some conversion and migration to a common platform to provide a basis for research. Even more important, other researchers, federal, regional, state, and local government agencies, and institutes will continue to collect information in or near the CLEANER site areas. Each data collection effort provides an opportunity to expand the scope of the CLEANER data set. The CLEANER program site leads might not have the authority to dictate everyone's data collection protocols within their geographic footprint. However, the availability of an open source standard, similar to those provided for software developers, can encourage and promote consistency in data collection. The open source standard could be provided and disseminated under the auspices of the CLEANER program. The CLEANER network of data sets should be available to all researchers with adequate recognition of those who collected them. Data should be widely available and be shared among the research community. Open standards and data sharing can be critical to the ultimate success and long term success of CLEANER.

The current cyberinfrastructure approach to achieving application integration is services-oriented architecture design, building on standards and tools developed from the web/grid services communities (e.g., the World Wide Web Consortium[3]). This approach is being developed for both NEON and CUAHSI HIS.

A focused effort to coordinate these activities could play a significant role in building a common cyberinfrastructure platform for integrating CLEANER (including the CUAHSI HIS), and NEON (and others), i.e., in building EON.

[3] *http://w3c.org.*

DISSEMINATION, OUTREACH, AND EDUCATION

Large-scale national observatories to assess the status of environmental resources provide opportunities to better understand environmental systems and natural and human-induced perturbations to these systems. This increased understanding should ultimately help water resource managers, for example, forecast the conditions of environmental resources much like the National Weather Service provides weather forecasts. Environmental forecasts might be the status of beach areas due to concerns over pathogens or nuisance algae blooms, adverse air quality events in urban areas (e.g., elevated ozone, particulate matter), turbidity events in water supplies, or the impacts of combined sewer overflows in waters adjacent to urban areas.

An improved forecasting capability should motivate increased interaction and communication with resource managers and engagement with the public about environmental resources and problems. This interaction and communication can benefit from improved programs in environmental education and outreach. If CLEANER and the other environmental observatory initiatives fail to transform environmental education and outreach, then they will fail to meet their full potential. The observatory initiative has the potential to make knowledge of the status of environmental resources a basic component of day-to-day life.

Given the level of investment and necessary commitment of funds and time needed to design, implement and operate the environmental observatories, it would seem critical that this large-scale science and engineering initiative should be incorporated into science and engineering curricula at universities. Such an educational initiative would seem to be necessary to train the next generation of scientists and engineers on how to effectively use and to continue to improve the environmental observing systems. Furthermore, these networks will be able to convey and animate patterns and processes at spatial and temporal scales not currently possible. This, together with new sensors and other technologies associated with the environmental observatories, just might capture the imagination of younger scientists and help attract them to the fields of environmental engineering and science.

SOME NECESSARY CONDITIONS

The benefits derived from environmental observatories can only be realized if these observatories are a long-term undertaking. While planning efforts continue, it is important to consider and avoid pitfalls from such an undertaking. The potential benefits have been outlined in the previous chapters. Here we discuss possible "fatal flaws" to avoid should these environmental observatories be implemented. Prior to implementing the environmental observatory network program(s), it is critical to identify through scenario planning any flaw that would make untenable all or part of the program. Examples of fatal flaws for this observatory investment might include:

- lack of sufficient funding to create a network on a scale that is needed and resources to maintain and upgrade it over time;
- software security failure resulting in data loss or major delays in research;
- process failure in selecting research challenges;
- inappropriate location and scale of observatories (i.e., critical gaps in geographical coverage, inefficient use of resources on large, complex systems);
- loss of public and political support due to inability to connect research results with required actions and desired outcomes; and
- inability to train enough engineers and scientists with the interdisciplinary breadth required to operate CLEANER and address the future research challenges of CLEANER.

Fatal flaw analyses of possible scenarios such as these can help identify potential "surprises" that could reduce the benefits coming from environmental observatories. Such analyses can also help identify activities which if undertaken might reduce the likelihood of these possible fatal flaws occurring. For clarity, each of the above possible fatal flaw concerns are briefly discussed below.

Lack of Sufficient Funding

Given the short-term pressures on the availability of funds, lack of sufficient money to maintain these environmental observatories and the databases through the long-term is a realistic concern (Merali and Giles, 2005). The research community needs to be committed to the environmental observatories so that there is a willingness to use programmatic funds, if necessary, for their long-term maintenance and operation. Leveraging or cost-sharing strategies may be necessary to better ensure both short- and long-term funding. Every step must be taken to assure the public's return on the capital investment by securing operating funds sufficient for long periods as part of the capital plan. Expensive observing systems could quickly become useless if operating and maintenance monies become insufficient or unavailable to continue those observations on into the long-term future.

Also of potential concern is the source of such operating and maintenance funding. If operating and maintenance monies must come from the research budget of NSF normally available to individual investigators, it becomes a tradeoff between the benefits derived from CLEANER and those derived by individual scientists and engineers pursuing other research topics. Younger professors in particular are vulnerable to any reductions in research funding that is essential for graduate student support and hence to their professional careers. If maintaining and upgrading the CLEANER environmental observatory network takes away funds from individual research programs, will the gain in understanding from CLEANER be worth any future loss to other environmental science and engineering educational and research programs not directly tied to CLEANER?

Software Storage and Security

The success of the observatory approach depends on reliable long-term storage and management of time-series and other data. Plans for creating and maintaining databases should consider the need to port databases to new hardware as it is developed in the future and as current technology becomes obsolete. It is critical that collaborators cooperate, share data, and make timely entries into applicable databases. Quality assurance information should be incorporated into the database maintenance program so proper interpretation of observations is ensured. Another challenge is to maintain the accessibility and flexibility of ever-increasing data and databases as well as the interfaces that maximize their use. The security of these data is critical to the identification of long-term trends, yet all databases need to be accessible to multiple users at multiple sites.

Process Failure for Selecting Research Challenges

Selection of what to observe is an important issue. Failure to measure, collect, and store the values of priority environmental parameters will restrict future research opportunities. Considerable attention needs to be given to the proper identification and selection of the data to be obtained over space and time to address the important current and future environmental resource and ecosystem management issues. In this regard it is critical that all relevant disciplines be active participants in CLEANER (e.g., geochemistry, environmental engineering, hydrology, microbiology, geomorphology, social sciences) to ensure that there will be a comprehensive examination of the problems that may need to be addressed and their data requirements. It is always a challenge to know what data (that may be of little or no significance today) we should be currently collecting for the benefit of researchers and resource managers in the distant future.

Mis-location of Observatories, Gaps in Geographical Coverage, and Appropriate Scale for Site Selection

We must be certain that observatories are put in the "right" places and that resources are used optimally. In a program such as CLEANER that focuses so fundamentally on water and human interactions with our environment, geographic coverage means that hydrology, and specifically water flows, may determine to a large extent the geographic coverage of observatories. Large river basins should be a focus of special emphasis for CLEANER because of their impact on surface water flows, water quality, and ecosystem functioning. (Furthermore, other observatory programs are not including them.) For example, an important area might be a large agricultural region where groundwater flows are critical to its economy. Major metropolitan areas are also candidates for better understanding and predicting the environmental-human interactions in our built environments. While it is likely that CLEANER will focus on large aquatic systems, resources may not be adequate to study very large, complex systems. There are important tradeoffs in site design and scale relative to available resources that the principal investigators of CLEANER will need to evaluate. Following the development of an important question to be addressed, a system should be selected for study that is large enough to address that question, but not too large to investigate effectively without wasting resources. Another tradeoff is should one region be selected to address all questions of importance, or should several regions be selected based upon their potential to address one or two of the critical questions? All of this implies that the CLEANER program should be driven by where the data will be of most scientific value and where the available resources can be used most cost-effectively, not just for geographical coverage.

Covering a range of spatial scales is also important. Smaller systems can serve as more isolated laboratories. For example, the Lake Tahoe basin has a long record of data collection, modeling, and research. This smaller system has the benefit of a very distinct and enclosed watershed and a centralized high alpine lake. For larger systems various "nested" monitoring approaches can be designed to provide both the larger and smaller watershed laboratories. The more detailed systems could be a size (<100 square miles) that is more responsive and reactive. Smaller systems are likely to be more useful when building and testing models and evaluating reactions to changing environmental conditions. By "nesting" within larger systems the analysis of the larger scale and far field impacts can also be evaluated concurrently.

Inability to Connect Research with Required Actions

All research proposals must be connected to an action plan that produces results and tests hypotheses and eventually makes a positive difference to human conditions. The sequence of converting data to information and then to knowledge and action must be thoroughly considered and planned before selecting from the many alternatives any particular scientific research program to undertake. Analysis and use of data need to be stressed, rather than simply collecting and archiving data. There is also a critical need to better communicate scientific and engineering findings with resource managers and the public. Public, and thus political, support for continuing these long-term observatories will be essential for their long-term success. Improved linkages with the social sciences will facilitate understanding the need for communication and the communication of findings to important stakeholders.

While not the mission of CLEANER, an outcome many stakeholders might wish from a successful and ongoing CLEANER program would be the establishment of environmental monitoring and management centers. These centers would have access to near real-time information and predictive models that together would provide early warnings of potential adverse hydrologic and environmental impacts due to natural or human activities. The establishment of an early warning system based on observation data, especially of resources or species under stress, could help identify emerging problems in time to change land and water management policies to prevent further degradation if not permit some restoration. Such an early warning system must be based not only on what is being observed, i.e., current data, but also on the research stemming from the long-term integrated data sets obtained from the environmental observatories.

In 1990, a multi-panel committee of the EPA's Science Advisory Board developed a ranking of risks to natural ecology and human welfare. This ranking turned out to be contrary to the public's perception of risks. From a scientific viewpoint, loss of biological diversity was a higher risk than were ground water pollution and presence of radionuclides (EPA, 1990). Environmental observatories, and indeed these potential environmental monitoring and management centers, must focus on the risks perceived by both the public and the scientific community if emerging problems are to be detected in a timely manner.

Inability to Train Enough Engineers and Scientists

As discussed above, training future engineers and scientists in the science of remote observing systems and associated cyberinfrastructure will be critical to the long-term success of CLEANER and other observing systems. Training is the job of universities, and graduate programs in environmental subjects cost money. Environmental and ecological engineering departments in universities need to attract bright graduate students to undertake such studies. Training grants and fellowships, perhaps similar to those provided by the public health service that resulted in strong environmental engineering programs of the 1960s, may need to be considered.

SUMMARY

Planning and development activities are underway by the NSF for several national environmental observatory systems. These systems each have somewhat different goals and missions, but there is also considerable overlap in terms of scope and components of research and outreach activities. In addition, there is a wealth of federal, regional, state, and local environmental monitoring in the United States. These monitoring programs are typically closely linked to the mission of the coordinating agency and are coupled with management of natural resources. It is important for CLEANER to be well integrated into the existing and planned networks of the NSF environmental observatories and various federal, regional, state, and local monitoring activities as well.

CLEANER is in a unique position to catalyze linkages between the national science-based observing systems and governmental monitoring efforts. CLEANER is distinct from the other proposed environmental observatories due to its focus on interactions between the natural environment and engineered systems, and particularly human-stressed systems. As a result, CLEANER should be closely aligned with applied issues that are of national significance and associated with government environmental monitoring and assessment programs. If properly coordinated, CLEANER could add considerable value to ongoing government monitoring efforts through data management, and the application of models and other analysis tools. In turn through proper coordination and linkages, CLEANER could add value to the data obtained from other observatories as it focuses on engineering and more applied issues.

To facilitate coordination of the national environmental observatories, the NSF should strongly consider establishing a parent organization that could be termed something like the "Environmental Observatory Networks" or EON, which would be responsible for cyberinfrastructure development, educational activities, outreach, and other shared activities across the NSF observatory programs. EON (or some alternative entity, to be determined by the NSF) would facilitate collaboration and coordination among the observatory programs and minimize redundancy. To facilitate and improve linkages between CLEANER and existing governmental assessment programs (federal, regional, state, local), a series of workshops, inter-agency agreements, and other collaborative activities is recommended.

There are several areas of common interest across the NSF environmental observatories, including cyberinfrastructure (e.g., data, software, sensors, models), education, and outreach. These activities and initiatives should be coordinated and joint programs should be established among and involving all observatories. A comprehensive approach to building an efficient, secure, scalable, and extensible environmental observing system (or systems) will require careful design across all three areas. A critical activity of national environmental observatories will be outreach to water resource managers and the public, as well as training the next generation of scientist and engineers in the "science of environmental observing systems."

The committee supports the concept of CLEANER and recommends that it proceed with planning and coordination activities. This planning should include an analysis of potential "fatal flaws" that could limit, or possibly negate, the benefits expected from CLEANER. Should the NSF become assured that these potential pitfalls can be avoided or mitigated, CLEANER has the potential of supplementing existing national science-based observing systems and governmental environmental assessment efforts, especially those focused on the interactions between the natural environment and engineered-human systems. A successfully operating environmental observatory network could transform the environmental engineering profession and increase its already considerable contributions to society.

References

Allan, J. 2004. Landscapes and riverscapes: The influence of land use on stream ecosystems. Annual Review of Ecology, Evolution, and Systematics 35:257-84.

Cloern, J., T. Powell, and L. Huzzey. 1989. Spatial and temporal variability in South San Francisco Bay (USA). II. Temporal changes in salinity, suspended sediments, and phytoplankton biomass and productivity over tidal time scales. Estuarine, Coastal, and Shelf Science 28(6):599-613.

DiLorenzo, J., R. Filadelfo, C. Surak, H. Litwack, V. Gunawardana, and T. Najarian. 2004. Short-term visibility of water quality parameters in two shallow estuaries of North Carolina. Estuaries 22:814-23.

EPA (Environmental Protection Agency). 1990. Reducing Risk: Setting Priorities and Strategies for Environmental Protection SAB-EC-90-021. Washington, D.C.: EPA.

Merali, Z., and J. Giles. 2005. Databases in peril. Nature 435:1010-11.

NRC (National Research Council). 2001. Grand Challenges in Environmental Sciences. Washington, D.C.: National Academy Press.

NRC. 2003. Science and the Greater Everglades Ecosystem Restoration: An Assessment of the Critical Ecosystem Studies Initiative. Washington, D.C.: National Academies Press.

NRC. 2004a. NEON: Addressing the Nation's Environmental Challenges. Washington, D.C.: National Academies Press.

NRC. 2004b. Confronting the Nation's Water Problems: The Role of Research. Washington, D.C.: National Academies Press.

NSF (National Science Foundation). 2005. Sensors for Environmental Observatories: Report of the NSF Sponsored Workshop December 2004. Arlington, VA: NSF.

Palmer, M., E. Bernhardt, E. Chornesky, S. Collins, A. Dobson, C. Duke, B. Gold, R. Jacobson, S. Kingsland, R. Kranz, M. Mappin, M. Martinez, F. Micheli, J. Morse, M. Pace, M. Pascual, S. Palumbi, O. Reichman, A. Simons, A. Townsend, M. Turner. 2004. Ecology for a crowded planet. Science 304(5675):1251-52.

SWAQ (Subcommittee on Water Availability and Quality). 2004. Science and Technology to Support Fresh Water Availability in the United States. Washington, D.C.: Executive Office of the President, National Science and Technology Council, Committee on Environmental and Natural Resources.

Acronyms

ARS	Agricultural Research Service
CLEANER	Collaborative Large-scale Engineering Analysis Network for Environmental Research
COTS	commercial off-the-shelf
CUAHSI	Consortium of Universities for the Advancement of Hydrologic Science
EON	Environmental Observatory Networks
EPA	Environmental Protection Agency
FS	Forest Service
GEON	Geosciences Network
GIS	geographic information system
GOOS	Global Ocean Observing System
HIF	Hydrologic Instrumentation Facility
HIS	Hydrologic Information System
IECS	intelligent environmental control system
LOOKING	Laboratory for the Ocean Observatory Knowledge Integration Grid
LTER	Long-Term Ecological Research
MREFC	Major Research Equipment and Facilities Construction
NAE	National Academy of Engineering
NAWQA	National Water Quality Assessment
NEON	National Ecological Observatory Network
NOAA	National Oceanic and Atmospheric Administration
NRC	National Research Council
NSF	National Science Foundation
NWIS	National Water Information System
OOI	Ocean Observatories Initiative
REMAP	Regional Environmental Monitoring Assessment Program
STORET	storage and retrieval
SWAQ	Subcommittee on Water Availability and Quality
USDA	U.S. Department of Agriculture
USGS	U.S. Geological Survey
WATERS	Water Environmental Research Systems
WEBB	Water, Energy, and Biogeochemical Budgets
WSTB	Water Science and Technology Board

Appendixes

Appendix A

WATER SCIENCE AND TECHNOLOGY BOARD

R. RHODES TRUSSELL, *Chair,* Trussell Technologies, Inc., Pasadena, California
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DARA ENTEKHABI, Massachusetts Institute of Technology, Cambridge, Massachusetts
GERALD E. GALLOWAY, Titan Corporation, Arlington, Virginia
PETER GLEICK, Pacific Institute for Studies in Development, Environment, and Security, Oakland, California
CHARLES N. HAAS, Drexel University, Philadelphia, Pennsylvania
KAI N. LEE, Williams College, Williamstown, Massachusetts
JAMES K. MITCHELL, Virginia Polytechnic Institute and State University, Blacksburg
CHRISTINE L. MOE, Emory University, Atlanta, Georgia
ROBERT PERCIASEPE, National Audubon Society, New York, New York
LEONARD SHABMAN, Resources for the Future, Washington, D.C.
KARL K. TUREKIAN, Yale University, New Haven, Connecticut
HAME M. WATT, Independent Consultant, Washington, D.C.
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ANITA A. HALL, Program Associate
DOROTHY K. WEIR, Research Associate

Appendix B

Biographical Sketches for Committee on the Collaborative Large-scale Engineering Analysis Network for Environmental Research (CLEANER)

Daniel P. Loucks (NAE), *Chair*, is a professor in the Department of Civil and Environmental Engineering at Cornell University where he applies systems analysis, economic theory, ecology, and environmental engineering to problems in regional development and environmental quality management. At Cornell, he has served as Chair of the Department of Civil and Environmental Engineering and as Associate Dean for Research and Graduate Studies in the College of Engineering. Dr. Loucks has also worked as a consultant to private and government agencies and various organizations of the United Nations, World Bank, and NATO on regional water resources development planning throughout the world. He has been a member of various committees of the national Research Council and currently serves on the Committee on Integrated Observations for Hydrologic and Related Sciences. Dr. Loucks was elected to the National Academy of Engineering in 1989. He received his M.F. in forestry from Yale University and his Ph.D. in environmental engineering from Cornell University.

Pedro J. Alvarez is the George R. Brown Professor of Civil and Environmental Engineering at Rice University and the new chair of the department. He previously taught at the University of Iowa, where he also served as associate director for the Center for Biocatalysis and Bioprocessing and as Honorary Consul for Nicaragua. Dr. Alvarez's research interests are related to the applications and implications of biological processes in natural and engineered systems, including bioremediation and phytoremediation of sites contaminated with hazardous wastes. He was inducted into the American Academy of Environmental Engineers in 1995 and is also the president elect for the Association of Environmental Engineering and Science Professors. Dr. Alvarez received a B. Eng. degree in Civil Engineering from McGill University and M.S. and Ph.D. degrees in environmental engineering from the University of Michigan.

Mary Jo Baedecker is a scientist emeritus at the U.S. Geological Survey. She previously served as Chief Scientist for Hydrology where she provided oversight for the National Research Program in the hydrologic sciences and represented the hydrology discipline in long-range program planning at the USGS. Dr. Baedecker's research interests include the degradation and attenuation of organic contaminants in hydrologic environments. She is a member of the

NRC's Water Science and Technology Board and has served on several NRC committees including the Committee on Ground Water Cleanup Alternatives and the Committee on Source Removal of Contaminants in the Subsurface. Dr. Baedecker holds a B.A. in chemistry from Vanderbilt University, an M.S. in chemistry from the University of Kentucky, and a Ph.D. in geochemistry from George Washington University.

James W. Boyd is Senior Fellow and Director of the Energy and Natural Resources Division at Resources for the Future. Dr. Boyd's research is in the fields of environmental regulation, law, and economics, focusing on the analysis of environmental institutions and policy. Specific areas of expertise include water regulation, environmental and product liability law, incentive-based regulation, and ecological benefit and damage assessment. His current research focuses on the development of environmental benefit indicators for use in both environmental management and national welfare accounting. Dr. Boyd has been a visiting faculty member at the Olin Business School, Washington University, St. Louis, and he currently serves on a U.S. Environmental Protection Agency Science Advisory Board on Valuing the Protection of Ecological Systems and Services. He has been a consultant to, among others, the World Bank, the European Commission, the Harvard Institute for International Development, and various government agencies. Dr. Boyd holds a B.A. in history from the University of Michigan and a Ph.D. in public policy and management from the Wharton School at the University of Pennsylvania.

Richard A. Conway (NAE) retired from Union Carbide Corporation as a senior corporate fellow. His areas of expertise include industrial ecology, petrochemical wastewater treatment, hazardous and solid waste management, environmental risk analysis of chemical products, and site restoration and remediation. Mr. Conway's work has encompassed research planning and evaluation and policy and regulation development. He has served on multiple NRC commissions, committees, panels, and boards and was elected to the National Academy of Engineering in 1986. Mr. Conway has also served on science advisory boards for the Environmental Protection Agency and Department of Defense and received career recognition awards from the Society of Environmental Toxicology and Chemistry and the American Academy of Environmental Engineers. He received a B.S. in public health in 1953 from the University of Massachusetts and an M.S. in sanitary engineering from the Massachusetts Institute of Technology in 1957.

John W. Day is Distinguished Professor Emeritus in the Department of Oceanography and Coastal Science at Louisiana State University and is a leading expert on wetland ecology, wetland-river interactions and water quality, coastal zone ecology, and ecological modeling. Some of his current research projects include utilizing Mississippi River diversions for nutrient management in a Louisiana coastal watershed, mitigating non-point source pollution in urban watersheds, and developing nutrient standards for Louisiana waters. Dr. Day is Chair of the National Technical Review Committee that oversees and reviews the Louisiana Coastal Area Project to restore the Mississippi Delta. He has a B.A. and M.S. in zoology from LSU and a Ph.D. in marine and environmental sciences from the University of North Carolina.

Charles T. Driscoll is University Professor in the Department of Civil and Environmental Engineering at Syracuse University where he also serves as the director of the Center for Environmental Systems Engineering. His teaching and research interests are in the area of environmental chemistry, biogeochemistry, and environmental quality modeling. A principal research focus has been the response of forest, aquatic, and coastal ecosystems to disturbance, including air pollution, land use change, and elevated inputs of nutrients and mercury. Dr. Driscoll is currently the principal investigator of the National Science Foundation's LTER project at the Hubbard Brook Experimental Forest in New Hampshire. He received his B.S. degree in civil engineering from the University of Maine and his M.S. and Ph.D. in environmental engineering from Cornell University.

Tony R. Fountain is director of the Cyberinfrastructure Laboratory for Environmental Observing Systems (CLEOS) at the San Diego Supercomputer Center (SDSC) of the University of California, San Diego. SDSC serves as an international resource for data cyberinfrastructure and focuses on data-oriented and computational science and engineering applications. Dr. Fountain's group is involved in a number of sensornet and observation system projects that aim to address the issue of sensor network management and data accessibility. His research focuses on data mining, machine learning, and computational infrastructure for a variety of science and engineering applications. Of particular interest are applications in ecology and environmental science involving sensor networks, complex data analysis, and real-time decision support. Dr. Fountain is a member of the National Ecological Observatory Network's (NEON) Facilities and Infrastructure Committee and advises the development of NEON's communication and information technology. He holds a B.S. in cognitive psychology and statistics and a B.S. in computer science and mathematics from North Arizona University. Dr. Fountain received his M.S. and Ph.D. in computer science from Oregon State University.

Edwin E. Herricks is professor of ecological engineering in the Department of Civil and Environmental Engineering at the University of Illinois at Urbana-Champaign. His areas of expertise include aquatic ecology and stream ecosystem and watershed management. Dr. Herrick's current research includes evaluation the effect of climate change scenarios on fisheries; restoration of streams in urban areas, including the development of ecological engineering concepts for watershed management; and development of an integrated hydrologic, geomorphic, and ecological classification system for watershed management. He has served on several NRC committees addressing issues such as endangered species in the Platte River, the legacy of radiation problems at Hanford, WA, and management of the Upper Mississippi River Navigation Project. Dr. Herricks has written numerous articles and papers on the broad theme of improving engineering design and environmental decision making. He holds a B.A. in zoology and English from the University of Kansas, an M.S. in sanitary/environmental engineering from The Johns Hopkins University, and a Ph.D. in biology from Virginia Polytechnic Institute and State University.

Robert J. Huggett recently retired as Professor of Zoology and Vice President for Research and Graduate Studies at Michigan State University. He also is Professor Emeritus of Marine Science at the College of William and Mary. Dr. Huggett's aquatic biogeochemistry research has involved the fate and effects of hazardous substances in aquatic systems with a focus on hydrophobic chemicals and their partitioning between sediment and pore water. From 1994 to 1997, Dr. Huggett was the Assistant Administrator for Research and Development for the United States Environmental Protection Agency. He has served on many NRC committees, is a past member of the WSTB, and a current member of the Board on Environmental Studies and Toxicology. Dr. Huggett has an M.S. degree in marine chemistry from the Scripps Institution of Oceanography and a Ph.D. in marine science from the College of William and Mary.

Timothy K. Kratz is the director of the Trout Lake Station at the Center for Limnology at the University of Wisconsin. His research focuses on the long-term, regional ecology of lakes; carbon dynamics in lakes; lake metabolism; and the formation and ecology of kettle-hole peatlands. Dr. Kratz is a principle investigator for the North Temperate Lakes LTER and has served on the LTER's Executive Committee. He has participated on the NRC's Committee to Assess EPA's Environmental Monitoring and Assessment Project and the Committee on Grand Canyon Monitoring and Research. Dr. Kratz earned his B.S. in botany from the University of Wisconsin, Madison, his M.S. in ecology and behavioral biology from the University of Minnesota, and his Ph.D. in botany from the University of Wisconsin.

Jeffrey M. Lauria is a vice president of Malcolm Pirnie, Inc., a century-old New York-based firm of civil and environmental engineers and scientists specializing in water issues. As National Director of Water Resources, Dr. Lauria directs large-scale program management and engineering master plans for wastewater, wet weather, watershed, and water quality projects. He also has comprehensive national and international experience in wastewater, drinking water, and stormwater treatment processes and related expertise in hydraulic, hydrologic, water quality, and mathematical modeling to support decision optimization at more than 200 project locations. Dr. Lauria has also served as a technical adviser to several state and local governments and on scientific and managerial councils from the private sector. He recently served on the NRC's

Committee on Water Quality Improvement for the Pittsburgh Region. Dr. Lauria received a B.E. in civil engineering from Manhattan College, and an M.E. and Ph.D. in environmental engineering from Manhattan College and Polytechnic University, respectively.

Judith L. Meyer is Distinguished Research Professor at the University of Georgia's Institute of Ecology. Her expertise is in river and stream ecosystems with emphasis on nutrient dynamics, microbial food webs, riparian zones, ecosystem management, river restoration, and urban rivers. Dr. Meyer is a past member of the WSTB, a current member of the Board on Environmental Studies and Toxicology, and has served on multiple NRC committees. She currently serves on the Environmental Processes and Effects Committee of the EPA's Science Advisory Board and on the Independent Science Board of the California Bay Delta Authority. Dr. Meyer also chairs the Scientific and Technical Advisory Committees and is on the Board of Directors of American Rivers and Upper Chattahoochee Riverkeeper. She received a Ph.D. in 1978 from Cornell University.

Tavit O. Najarian is president of Najarian Associates, a civil engineering and environmental consulting firm. Dr. Najarian is an expert in the field of water resources. Over the past 25 years, he has been involved with the development, adaptation, and application of mathematical models for hydrodynamic and water quality simulations of aquatic systems. Dr. Najarian has particular expertise in applying such models in studies of wasteload allocation and regional planning of stormwater runoff and estuarine eutrophication dynamics. He also serves as a consultant on hydraulic and environmental issues related to large-scale planned residential, commercial, industrial, and waterfront projects. Dr. Najarian earned his B.C.E. from American University in Beirut, Lebanon, his M.S. in civil engineering from Northeastern University, and his Sc.D. in hydrodynamics and water resources from the Massachusetts Institute of Technology.

Charles R. O'Melia (NAE) is the Abel Wolman Professor of Environmental Engineering and Chair of the Department of Geography and Environmental Engineering at Johns Hopkins University. His professional experience includes positions at Hazen & Sawyer Engineers, University of Michigan, Georgia Institute of Technology, Harvard University, and the University of North Carolina, Chapel Hill. His research interests are in aquatic chemistry, environmental fate and transport, predictive modeling of natural systems, and the theory of water and wastewater treatment. He is a member of the National Academy of Engineering and past member of the Water Science and Technology Board and the Board on Environmental Studies and Toxicology. He has served on numerous NRC committees, including the Committee on Research Opportunities and Priorities for EPA, the Committee on Wastewater Management for Coastal Urban Areas, and the Committee on Water-Treatment Chemicals, and he was chair of the Committee to Review the New York City

Watershed Management Strategy. He received a B.C.E. from Manhattan College and an M.S.E. and Ph.D. in sanitary engineering from the University of Michigan.