Watershed Management and the Emerging Environmental Cyberinfrastructure

U. Sunday Tim

Department of Agricultural and Biosystems Engineering
Iowa State University
Ames, Iowa 50011
Email: <tim@iastate.edu>

The last several decades have witnessed a paradigm shift in environmental planning and watershed management from a top-down government-agency-driven process toward a more collaborative, grass-roots approach that includes stakeholder participation, problem solving, and consensus building. Rather than focusing on specific pollutants, pollution sources, or specific areas within the watershed landscape, the new community-based approach (a) fosters a coordinated and efficient implementation of management programs to reduce pollutant discharges, maintain and improve water quality, and restore valuable habitats; (b) establishes local priorities within the context of regional and national goals and coordinates private and public actions; (c) integrates the abiotic and biotic components as well as the human and economic factors into the planning and management decisions; (d) focuses on quantifiable risks and benefits and measurable outcomes; and (e) establishes a process for involving non-governmental organizations and citizens through formal and informal meetings. Under this approach, the watershed represents an appropriate unit or hydro-political boundary for unifying the planning and management process and for producing the desired outcomes (Thorud et al. 2000; NRC 1999).

The watershed management approach has been heralded as an innovative approach to maintaining the integrity and functioning of terrestrial and aquatic ecosystems. Defined by the U.S. Environmental Protection Agency (USEPA) as a "coordinated framework for environmental management that focuses public and private sector efforts to address the highest priority problems within hydrologically defined geographic areas" (USEPA 1993), the elements of a watershed management approach include: (a) delineation of the landscape into hydrologically and culturally homogeneous units defined by a combination of hydrographic, physiographic, and human factors; (b) development and implementation of a sequence of management options—both tactical and strategic—to guide regulatory and non-regulatory actions within the defined units;

and (c) establishment of processes for involving public agencies, external and internal stakeholders, and the general public.

The watershed approach to environmental planning and water resources management is not new. Indeed it can be traced back to the 1880s when John Wesley Powell, the second director of the U.S. Geological Survey, proposed organizing settlements in the U.S. West around watersheds. In his 1878 *Report on the Lands of the Arid Region of the United States*, Powell believed that this organizing principle will not only provide appropriate governing entities, but also can facilitate the management and conservation of scarce resources. Powell's utopian vision also emerged during the first half of the 19^{th} century as awareness for resource overuse and water pollution increased. During this period, the Inland Waterways Commission, established in 1907 by President Roosevelt, suggested to Congress the concept of adopting a watershed-based strategy to effectively manage river systems for flood control, hydro-energy production, navigation, and drinking water supply. The second half of the 19^{th} century further witnessed an increasing emphasis on water quality improvements using watersheds as unifying management units. This provided the context for environmental legislation such as the Federal Water Pollution Control Act of 1956, the Water Quality Act of 1965, and many others thereafter.

Recently, the USEPA has reemphasized the importance of watersheds and the watershed management approach. In its 2005 report entitled "*Community-based Watershed Management: Lessons from the National Estuary Program*" the USEPA delineated five key elements of a community-based management approach that include (see Fig. 1): (a) identifying pollution problems within the watershed unit; (b) investigating probable sources and causes of the problem; (c) instigating probable solutions to the problem, (d) implementing cost-effective management strategies; and (e) communicating, sharing and disseminating the results to the general public (USEPA 2005).

Each of these elements of a community-based watershed management approach stands to benefit greatly from emerging cyberinfrastructure (CI) technologies for the environmental sciences. Broadly defined as "set of reliable, well-established, interoperable connections of electronic hardware and software that allows people to discover, learn, teach, collaborate, disseminate, access, and preserve knowledge in their domain" (Atkins et al. 2003), a CI technology integrates: high-performance hardware systems for computing, federated spatio-temporal databases, distributed and digitally-enabled sensor networks and observatories, and interoperable suite of software and middleware tools and services. It provides essential tools and infrastructure to create, archive, analyze, visualize, and disseminate environmental data, information and knowledge.

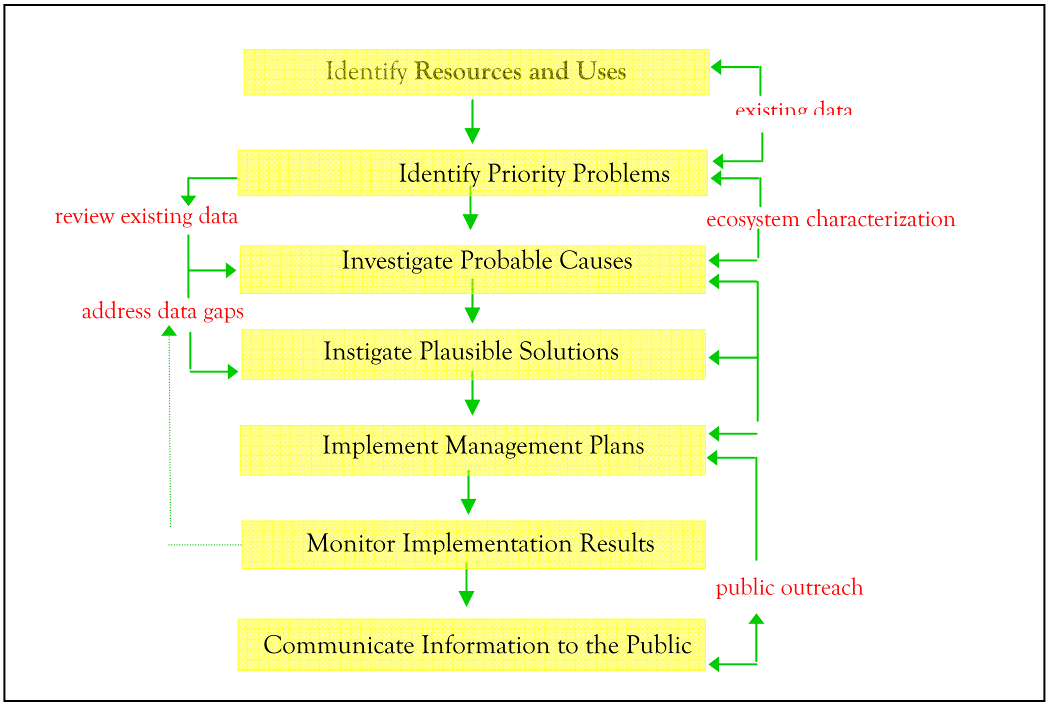


Figure 1: Elements of a community-based watershed management approach
(Source: *USEPA, 2005*)

Because many aspects of environmental planning are observationally oriented, incorporate multidimensional simulation modeling and visualization tools, and are highly collaborative, CI technologies offer promisingly new vision for enhancing research and environmental decision-making process. It does so by allowing scientists and resource managers to create, archive, analyze, share, and disseminate data and discuss their insights, observations and results in a more efficient manner. In community-based watershed management more specifically, CI provides new opportunities to integrate state-of-the-art computational tools and algorithms, geospatial technologies such as geographic information systems (GIS), and observational data from real-time sensors and federated databases into powerful decision support systems for planning watershed protection programs. The revolutionary potential of CI for watershed management is in providing distributed computational resources to describe, archive, and disseminate data and services (NSF, 2003).

The remainder of this Watershed Update will examine the potential role of CI technologies in environmental sciences focusing on three key elements of a community-based watershed management approach: (a) data collection and data management, (b) delineation of watershed problem areas for implementation of best management practices (BMPs) and remedial strategies, and (c) public outreach and stakeholder participation. The central theme of this Watershed Update is that, despite current and future technical and institutional challenges, cybertools and CI technologies for the environmental sciences stand poised to transform watershed management programs, enabling scientists and resource managers to investigate complex human-environmental systems in new and unimaginable ways.

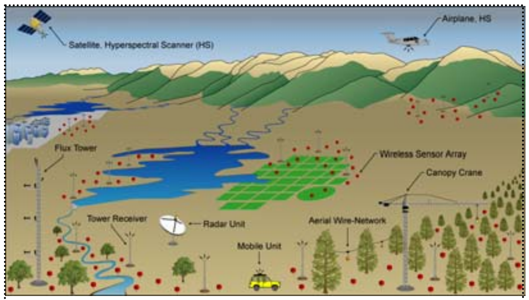
CI-mediated data collection and data management

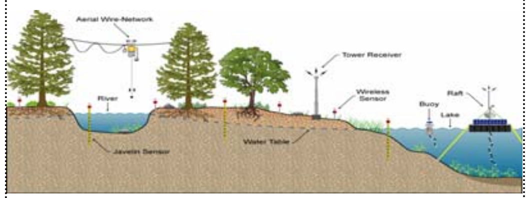
Comprehensive, reliable and readily accessible data is critical to an effective community-based watershed management program. In its report ***Watershed Management – Better Coordination of Data Collection Efforts Needed to Support Key Decisions***, the General Accounting Office (GAO) noted that *"The availability to decision makers of timely, reliable, and complete data about the nation's waters has significant environmental and financial implications"* (GAO, 2004). In assessing the data demands of the federal Clean Water Act's TMDL program, the report also stated: *"Water quality data, for example, are critical for determining which waters do not meet state's standards and must, therefore, be targeted for potentially expensive cleanup. Similarly, decision makers need reliable and comprehensive data on the quantity of the nation's water resources to support increasingly important – and contentious – decisions about how to allocate limited water resources among sates and among a variety of competing uses"*. From screening waters and watersheds for potential pollution problems to evaluating the effectiveness of BMPs and other remedial strategies, credible and high-quality data is critical to community-based watershed management programs. Thus the emerging CI technologies should help narrow the data shortage gap through advances in remote and real-time data acquisition networks; tools for fusion, storage and archiving of data; and computing power and algorithms for the synthesis, analysis and visualization of the data. For example, recent developments in eco-hydrologic observatories, including distributed sensor and networks, offer new opportunities for observation-driven analysis and management of complex watershed problems.

As an example, the National Ecological Observatory Network (NEON), a recent initiative by the National Science Foundation, establishes a continental-scale organization and platform for integrated studies on natural processes at varying space and time scales. Like other observatories, including the Collaborative Large-scale Engineering Analysis Network for Environmental Research (CLEANER) and the Geosciences Network (GEON), NEON is designed to provide the resources and infrastructure for ecological research that eventually will improve our understanding of the natural world, enhance our ability to predict consequences of natural and human-induced changes to the biosphere, and inform ecological decision-making. With sophisticated infrastructure for comprehensive, integrated measurement and analysis of ecological systems (see for example Fig. 2), the NEON will provide compatible datasets for addressing complex issues related to terrestrial biogeochemical cycling, biodiversity and ecosystem states and services, land use dynamics, and the ecology of infectious diseases. Ecological information from NEON observatories should provide critical inputs for parameterizing ecosystem models and for forecasting changes in watershed conditions due to anthropogenic perturbations (NRC 2003). In general, a CI for the environmental sciences that integrates data from distributed observatory networks has the potential to inform and support community-based watershed management, significantly enhancing the capacity of scientists and resource managers to collect critical environmental data from geographically disparate sources; fuse and manage the data; and analyze and visualize the data (Estrin et al. 2003).

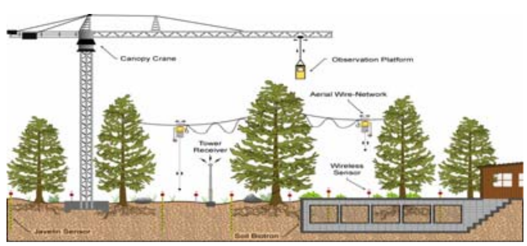
CI-enhanced delineation of watershed problem areas

Important advances in environmental research crucial to improving community-based watershed management have been brought near by a "perfect fusion" of sustained advances in scientific understanding of interrelated physical and biogeochemical processes; mathematical algorithms; and scientific software engineering. Simulation modeling has attained paramount status in many areas of science and engineering. Models are effective integrators of assessment data and related research activities, including the results of process-level studies. Indeed they provide a quantitative vehicle to test our understanding of complex natural and managed ecosystems. Models offer the best near-term hope for progress in addressing a number of complex problems associated with watershed management. For example, models (a) allow prediction of watershed responses to natural and human-induced changes at different time and space scales, (b) are essential for selecting efficient and cost-effective environmental monitoring programs, (c) allow transferability of results across space and time scales, and (d) facilitate outreach and stakeholder participation through consensus building and collaborative decision-making. However, the high level of synthesis and analysis required to address challenging issues in watershed management demands new analytical tools and model algorithms that exploit the increasingly flexible computing infrastructure and ontology (Foster and Kesselman 1999; Chen et al. 2005).





Aquatic Array



Terrestrial Array

Figure 2: Overview of the NEON infrastructure
(source: *www.neoninc.org*)

From integrated web-based simulation portals to sophisticated grid computing, a new era of interoperable, scalable and extensible computing infrastructure accessible to the entire science and engineering community has arrived (Foster 2002). By advancing the coordination and sharing of computing, application, data, and network resources, CI promises to change the way scientists tackle complex computational problems. For the watershed management community more specifically, high-end computing resources available through CI platforms will improve hydrologic forecasting and facilitate prediction of complex ecological processes that impact both natural and intensively managed watersheds. Perhaps the most exciting future is the rapidly advancing cybertools that transform the way in which scientists and resource managers collaborate virtually to solve complex watershed management problems, including identifying more effective adaptive management strategies to mitigate adverse effects of human footprints on air, water and land resources. Although significant challenges remain, an environmental CI should provide unprecedented opportunities to improve prediction of fundamental processes that occur in large-scale human-dominated environments over different time and space scales.

CI-mediated public outreach and stakeholder Participation

Public participation in local or community decision making is important in a democratic society. Indeed the public right to know about the environment and hazardous conditions in their communities has been an integral component of global environmental policy for many decades. In the United States, for example, the Emergency Planning and Community Right-to-Know Act of 1998 include provisions to increase citizen environmental literacy and ensure real-time access to environmental information at the local scale. The normative argument is that an environmentally literate citizen is likely to participate in the decision-making process either through good environmental stewardship or by supporting environmentally sustainable policies. The ability to access, analyze, visualize, and interpret disparate environmental data and to make informed and timely decisions are requisite elements of effective environmental management programs. For example, timely information about a recreational lake within an urban watershed can enable recreational lake users, resource managers, and lakeshore residents understand the cumulative implications of their day-to-day activities. on the lake's water quality. Other potential benefits of public outreach and citizen access to web-based information portals have been identified (Richards et al. 2003). These include: transmitting stakeholder preferences into decision making; rationalizing the decision making by collecting new ideas, alternatives, and information from affected stakeholders; and building support for the policy decisions.

To date, information and geospatial technologies such as the Internet and the GIS have provided the tools for public outreach and information sharing. Specifically, the Internet has offered a powerful medium for delivering valuable information to the public, anywhere and anytime. Initially confined to the research community, the Internet supports rapid, location-independent, and inexpensive multimedia-based communication and asynchronous interaction and collaboration. One advantage of the Internet is that it allows heterogeneous information to be displayed in a variety of ways, depending on the preference of the user. The GIS technology, on the other hand, offers users an unprecedented ability to acquire, manage, and dynamically interact with large amounts of geospatially referenced data. The ability of GIS to produce information in linked tabular and map form gives it an extraordinary flexibility. The integration of the Internet with GIS provides users with access to geospatial contents and capabilities, allowing them to interact and communicate through dynamic, digital maps. Geospatial digital libraries and interactive web-based mapping portals (commonly referred to as G-portals) offer users heterogeneous collection of georeferenced materials (e.g., maps, images, metadata, etc.) and sophisticated geospatial tools with which to analyze and visualize them.

An emerging CI for the environmental sciences can improve public outreach and stakeholder participation by enhancing (a) the integration of text, video, audio, imagery, and map information; (b) indexing, linking, and querying of distributed repositories of environmental/watershed landscape data; user interaction with the date through intuitive interfaces. Using service-oriented cybertools, environmental information can be defined as organized data that enables interpretation and insight, rather than disorganized collection of facts. The ability to integrate diverse and multimodal sources of watershed data and to apply appropriate metadata standards and privacy safeguards represents the Moonshot for an advancing environmental CI. Linking environmental modeling efforts to advanced sensor webs and information systems will provide new opportunities to initiate experimental forecasts of new watershed management variables, assess impacts and responses, and advance scientific knowledge of complex environmental systems.

Summary

Environmental planning in general and watershed management activities have changed remarkably during the last decade, due in large measure to the impact of increasingly powerful and pervasive information and communication technology. Today, simulation modeling of environmental processes within watersheds is as important to discovery and innovation as are theory and field observations. Advances in monitoring technologies, coupled with the availability of affordable mass data storage devices, have enabled the collection and federation of massive volumes of heterogeneous datasets needed to reveal new insights into complex human-environmental systems. Concomitantly, pervasive network and communication technologies have provided comprehensive and up-to-date access to a multitude of scientific resources and data. Collectively, these advances have helped to increase our understanding of environmental processes and to encourage citizen involvement in environmental decision-making. The future of community-based watershed management will increasingly rely on decision support systems, G-portals, and the advancing CI tools and services. Indeed, no resource management area stands to gain more from an advancing environmental CI than community-based watershed management, where scientists, resource planners and stakeholders are grappling with challenges that include characterizing the cycling of chemical and biological agents and understanding the dynamics of complex environmental systems.

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