

Special Issue on the Role of Systems Analysis in Watershed Management

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Watersheds are coupled human-natural systems (CHNSs) characterized by interactions between human activities and natural processes crossing a broad range of spatial and temporal scales. As stressed by a National Research Council (NRC) report (1999), watershed management poses an enormous challenge in the coming decades. The USDA and the EPA adopted a watershed approach to manage watersheds considering the interdependence among human, abiotic, and biotic components and the feedbacks that arise among management practices and their socioeconomic and environmental consequences. Concurrently, the attention of the environmental and water resources systems research community has evolved from the management of individual reservoirs, storm water, and aquifer systems to more integrated watershed or river basin systems. The application of systems analysis tools including simulation, optimization, and their integration offers an analytical mindset and a diversity of tools capable of addressing the complex challenges, which arise from human-natural interactions as well as communicating subsequent analyses to decision makers.

Methods of systems analysis have been integral to water resources systems planning and management since the 1960s. Initially, methods of simulation, mathematical programming, and decision analysis borrowed from the field of operations research were applied to water management challenges. Later, in the 1990s, innovations in complex systems arising, in part, from previous contributions from catastrophe theory in the 1970s and chaos theory in the 1980s began to be applied to the field of water resources planning and management. Today, the application of all of these methods that are termed a *systems approach* remains critical to our field. Perhaps now more than ever before, systems methods are needed to solve watershed management problems due to the emergence of numerous new concerns relating to stakeholder participation, environmental ethics, life-cycle analysis, sustainability, industrial ecology, and design for ecological (as opposed to engineering) resilience (Dobson and Beck 1999). Both practitioners and researchers routinely face watershed management challenges, including, for example, restoring degraded ecosystems to achieve a balance between human and nature, resolving conflicts over protection of open space and environmental quality and development

interests, and more generally accommodating within a watershed context water requirements for food, energy, and environment. Addressing these and other challenges requires the development of innovative systems concepts, methods, and algorithms for effective watershed management that can lead to both socioeconomic and environmental sustainability.

Recent scientific, technological, and institutional developments have already and will continue to facilitate integrated watershed systems analysis approaches. We expect innovations relating to a wide range of emerging areas to continue facilitating development of watershed systems analysis including, but not limited to (1) distributed watershed hydrologic modeling and digital watersheds facilitated by hydro-informatics with improved forecast capacity; (2) increasing availability of distributed and digital datasets [e.g., remote sensing, sensor-based monitoring, and cyberinfrastructure (CI)]; (3) multidisciplinary research efforts among hydrologists, ecologists, economists, systems experts, and others; (4) institutional and financial support for watershed restoration practices; (5) improvements in computational and optimization algorithms; and (6) evolution in our ability to integrate ecological, environmental, and social objectives into what was once only a more narrow economic analysis (Lund and Cai 2006). Perhaps the most important developments of all relating to the application of water resources systems methods involve advances in computational sciences that have made possible more advanced quantitative analyses and have moved research more broadly into modeling of a watershed or a river basin as an integrated system of, e.g., reservoirs, aquifers, wetlands, and drainage systems.

The goal of this special issue is to publish a representative set of papers focused on the field of watershed management modeling [see Zoltay et al. (2010)], which embraces and extends the myriad of recent advances described previously. This special issue is expected to serve the water resources management and planning community by highlighting the current state of some innovative research findings relating to applications of systems methods for solving various watershed management modeling problems. These problems include nonpoint source pollution management in urban or rural watersheds (papers by Jacobi et al., McGarity, Woodbury and Shoemaker, and Limbrunner et al.), water supply (paper by Giacomoni et al.), water allocation (papers by Riegels et al. and Pulido-Velazquez et al.), flood control (paper by Karamouz and Nazif), best management practices (BMPs) design and placement (papers by McGarity, Limbrunner et al., and Karamouz and Nazif), climate change adaptations (papers by Woodbury and Shoemaker and Karamouz and Nazif), total maximum daily load (TMDL) policy assessment (papers by Mirchi and Watkins and McGarity), and watershed system operations (papers by Anghileri et al. and Muste et al.). These problems are addressed through a number of real-world case studies, including both U.S. and international applications. Interestingly, a number of specific suggestions for policy and engineering design and system operations that arise from these case study problems are provided.

This set of papers also demonstrates the application of the state-of-the-art systems techniques to analyzing watershed management modeling problems. Classic linear, nonlinear, and dynamic programming models are still useful and exhibit potential for

research, particularly in creative formulations of mathematical programming models. As shown by Limbrunner et al., for a storm water and nonpoint sources pollution management problem, a linear programming optimization model can efficiently reproduce much of the same solution structure as contemporary evolutionary algorithms (EAs) and complex distributed watershed modeling, and a solution to the sediment management optimization problem can be efficiently found using a dynamic programming formulation. Mirchi and Watkins formulate a model using system dynamics (SD) for lake water quality management. Although SD is not new (Forrester and Senge 1980), as shown by Mirchi and Watkins, the SD-based model can simulate the interaction between socioeconomic subsystems and natural processes driving eutrophication, the key characteristic of CHNSs. Moreover, modeling watersheds as an integrated hydrologic-economic system (Cai 2008; Harou et al. 2009) illustrates specific instances of representing watersheds as CHNS for integrated water resources management based on both hydrologic and economic principles. Riegels et al. and Pulido-Velazquez et al. illustrate water price as an effective tool for water allocation in a river basin context and other related policy issues using integrated hydrologic-economic models.

Simulation-embedded optimization, particularly through EAs, has probably been the most widely used modeling tool for watershed management during the past decade (Nicklow et al. 2010). In this special issue, McGarity suggests a four-stage process supported by simulation and optimization models applied along with data processing and field monitoring for the development of a cost-effective strategy for watershed restoration. Others (Karamouz and Nazif, Woodbury and Shoemaker, and Limbrunner et al.) show the value of the application of genetic algorithms (GAs) and distributed or semidistributed watershed simulation models to optimize various management objectives for watershed management.

Challenges for water resources modelers and requests from model users involve the development of a physically based, institutionally realistic, and computationally tractable decision model for analyzing and evaluating watershed management alternatives. A distributed model for water resources management takes advantage of distributed hydrologic simulation modeling along with a decentralized decision model (Yang et al. 2009). Conventional management models adopt a centralized approach to explore systemwide feasible or optimal solutions, while decentralized decision models depict the actual spatial heterogeneity of decision making and coordination of individual decision making at a regional scale. Some decentralized models are termed multiple agent system (MAS) models, which are composed of multiple interacting autonomous agents within an environment while considering the interaction among individual decisions and the state of the environment (natural or built); others are defined as agent-based models (ABMs), which are computational models for simulating the actions and interactions of autonomous agents (both individual or collective entities such as organizations or groups) with a view to assess their effects on the system as a whole. By coupling MAS models or ABMs with physical models, natural processes, their environmental feedbacks, and societal responses can be analyzed in the context of CHNS. Giacomoni et al. demonstrate the value of coupling an ABM and an urban water supply simulation model. Water consumers and policy makers are defined as agents in the context of decision making over a long-term planning horizon. Anghileri et al. address a problem relating to operating multiple water-storing facilities in a watershed, which are usually operated independently of each other to meet specific operating objectives. They show that a coordinated mechanism can be designed to move

the current uncoordinated structure toward improved performance associated with ideal centralized operations.

Information technology, particularly hydroinformatics (Abbott 1991), has contributed to water resources management through the increased availability of remote sensing, geographic information system (GIS), and supercomputing technologies, as well as national coordination efforts such as those led by the Consortium of Universities for the Advancement of Hydrologic Science (CUAHSI). Muste et al. illustrate the implementation of a CI system to understand the ecological threats, shifts in soil conservation practices, and public perception of environmental health with preservation of the economic benefits of agricultural production at a watershed scale. CI involves the combined use of real-time sensing (temporally and spatially detailed), databases, high-performance computational platforms and computer models to enable understanding of processes, knowledge management, visualization, interaction, and collaboration in all science and engineering disciplines (U.S. National Science Foundation Research Council 2007). Jacobi et al. propose a framework for selecting the optimal combination of research, monitoring, and management actions using an approach that combines Bayesian inference and multiobjective linear programming to explicitly represent uncertainty in the assessment of effectiveness, costs, and the value of reducing uncertainty through research and monitoring.

A recent special issue of this journal (Volume 129, Number 4, 2003) on the topic of "TMDL Approach to Water Quality Management" was an analogous effort to highlight the use of water resource systems approaches to the more focused problem of managing watershed water quality. In that issue, Haith (2003) provides a definition of what we mean by the application of systems methods to watershed management along with several examples of its application. Judging from the tremendous advances in the application of systems methods contained in the current special issue in comparison with the previous special issue in 2003, the use of systems analysis in watershed management appears to have reached the growth stage.

In summary, the watershed along with its smaller hydrologic (subbasin) management units has emerged over time as a key unit for the implementation of solutions and execution of policy measures related to the needs of water resources management. Modeling watersheds as CHNS facilitates new model formulation and solution algorithms for both improved watershed management decisions and scientific understanding of human impacts on hydrologic processes (Vogel 2011) and the interdependency between human and natural systems in the watershed context. We anticipate that in the coming decades, systems analysis will take on a larger and more dominant role in watershed management than ever before given examples of recent advances described in this special issue combined with today's scientific, technological, and institutional support.

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