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Chapter 6

MODELING FOR WATERSHED PLANNING, MANAGEMENT, AND DECISION MAKING

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ABSTRACT

Water is both a natural resource and a public good that plays a critical role in a host of environmental processes and economic, social, and political activities. In recent years, watershed management practices that were once praised for their broad benefits to society have become the focus of harsh criticisms for their adverse and unexpected environmental or socioeconomic impacts. Thus, gaining an understanding of how various human activities affect watershed processes, and in turn how the variable nature of the hydrologic cycle affects humans' well-being, is essential for policy makers and watershed managers. Watershed models provide efficient tools for integrated studies of the major physical, socioeconomic, and political aspects of watersheds. For decades, water resources professionals have been developing and using models to address watershed problems, yet watershed models are still evolving in terms of approach, application, and ability to provide users with a comprehensive and reliable understanding of problems at a reasonable cost and within a specified timeframe. Early watershed modeling efforts were aimed mostly at representing hydrologic processes, but the need for interdisciplinary studies has led to increasing complexity and integration of environmental, social, and economic functions to facilitate a holistic understanding of watersheds and associated human activities. This chapter provides a chronological synthesis of watershed modeling approaches and applications. The rationale behind various watershed models is analyzed to demonstrate the interrelationship between decision making objectives, modeling approach, and applications. Finally, potential future directions for watershed modeling are highlighted.

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1. INTRODUCTION

The watershed has been widely acknowledged to be the appropriate unit of analysis for many water resources planning and management problems (e.g., McKinney et. al., 1999). However, many of the environmental processes and socioeconomic activities occurring within a watershed system are simply too complex, dynamic, and spatially variable to be precisely monitored and thoroughly understood. As population grows, continued human encroachment into natural systems seems inevitable, with expanding communities needing increased water supplies to carry on various development activities in the watershed. Paradoxically, both water shortage (drought) and overabundance (flooding) will become even more problematic for many communities, yet expectations will remain high for using water as a means of socioeconomic development and ecosystem conservation and enhancement. It is unlikely that these expectations can be met without the aid of analytical tools such as computer watershed models.

Watershed models are mathematical representations of watershed processes and affected socioeconomic and environmental systems. They have become a fundamental and integrated element of any engineering project or management practice that is deemed to alter diverse natural processes. Models help us gain insights into hydrological, ecological, biological, environmental, hydrogeochemical, and socioeconomic aspects of watersheds (Singh and Woolhiser, 2002), and thus contribute to systematized understanding of how watershed subsystems function (Lund and Palmer, 1997), which is essential to integrated water resources management and decision making (Madani and Marino, 2009).

There are numerous watershed models, having various levels of sophistication and providing diverse types of information, but all watershed models share one common characteristic, that is, they are all simplifications of actual watershed processes (Wurbs and James, 2002). Another common characteristic of all models is that they require data, or observations, in order for their parameters (i.e., equation coefficients) to be estimated accurately. The process of adjusting model parameters to obtain a good match between model output and real-world observations is called calibration. Additionally, an independent set of observations should be used to test, or verify, the calibrated model in order to evaluate the expected accuracy of model results. If the expected accuracy is not acceptable, additional data should be gathered, or a more simple model may be warranted. Although these steps of calibration and verification may be costly and time-consuming, they are critical to ensuring accurate results and fostering confidence in predicted outcomes.

The ubiquity of watershed models and breadth and scale of watershed-related problems that have been addressed using models make it difficult to cover all aspects of watershed modeling in a single chapter. The chapter focuses on illustrating the need for watershed modeling and introducing the reader to common modeling methods and approaches. A chronological synthesis of watershed modeling provides an overview of how modeling goals have evolved from describing only physical processes to the integration of social, economic, and environmental objectives in support of decision making. Example applications demonstrate the significance of watershed models, especially socioeconomic and hydroeconomic models that have been used successfully to provide comprehensive insights critical to watershed planning, management, and decision making. Finally, potential future directions for watershed modeling are noted.

2. The Need for Watershed Modeling

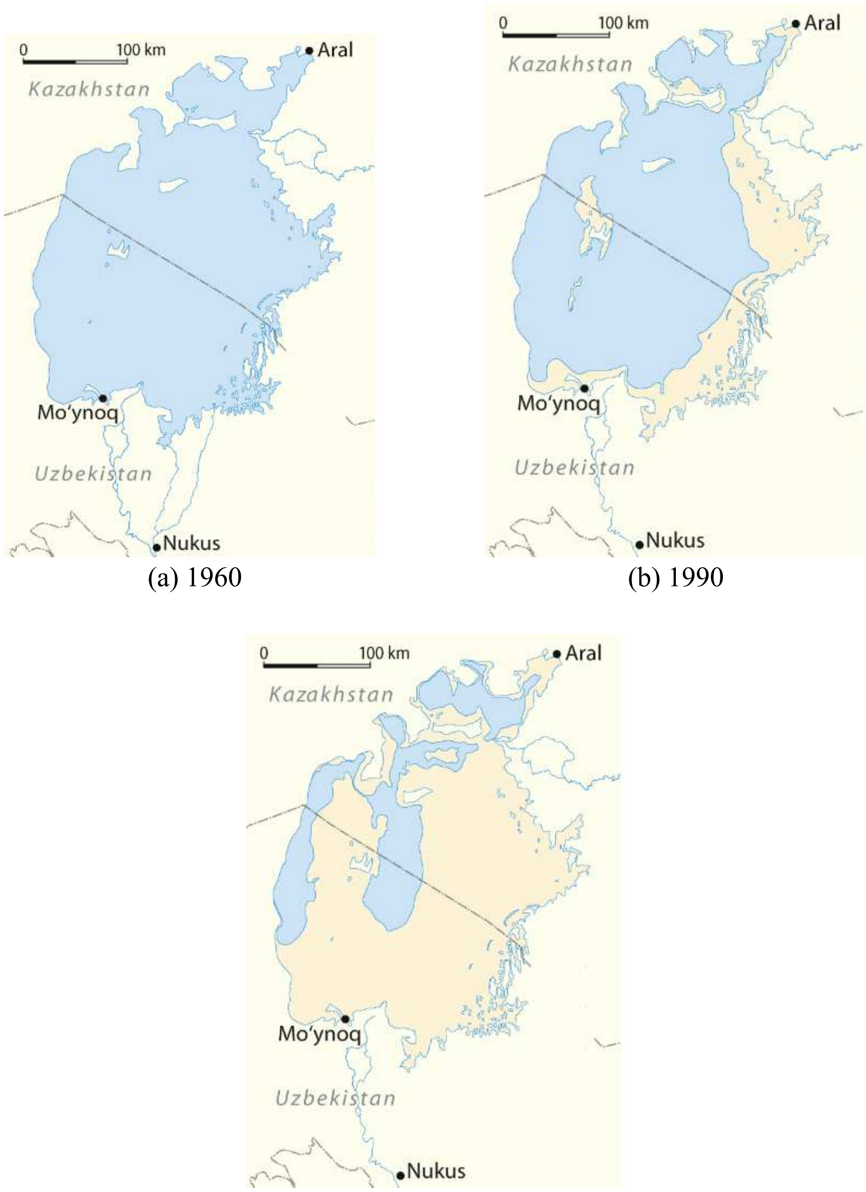
Watersheds are modeled to facilitate well-studied designs and informed management decisions. In engineering and management practices, it is important to understand complex interactions occurring today as well as predict impacts years, perhaps even decades, into the future. In recent years, watershed management practices that were once praised for their broad benefits to society have become the focus of harsh criticisms for their adverse and unexpected environmental or socioeconomic impacts. River channelization (Shen et. al, 1994; Langler and Smith, 2001), dam construction (Tullos, 2009), irrigation development (Dokhuvny and Stulina, 2001; Cai et. al., 2003; Schlüter et. al., 2006; Yoshinobu et. al., 2006), trans-basin water transfer (Madani and Marino, 2009), and hydraulic mining of rivers (Wright and Schoellhamer, 2004) are some examples of numerous cases of deteriorating socioeconomic and environmental conditions caused by lack of understanding of dynamic interactions of various watershed subsystems. Watershed models help us predict future impacts of projects and management policies, which in turn contributes to improved water resources system design, planning, and operation, and thus more sustainable water resources management. The following examples illustrate some of the environmental and socioeconomic challenges that can arise from improper watershed planning and management practices.

2.1. The Aral Sea

The Aral Sea basin is an example of an ecological and economic disaster resulting from water management practices that ignored long-run impacts at the watershed scale. An inland lake in the semi-arid and desert areas of Central Asia, the Aral Sea was once fed by a total average inflow of 109 cubic kilometers per year from the Amu Darya and Syr Darya rivers (Cai, et. al.2003; Yoshinobu et. al., 2006; Schlüter et. al., 2006). Extensive irrigation withdrawals, coupled with high water consumption in the basin (population 35 million), have caused the lake surface area to shrink to less than 50% its normal size (Figure 1). The lake is now appreciably shallower, and its salt concentration has tripled. Soil salinity has also increased in the basin due to irrigation practices. The consequences of the disaster are unfolding, within and beyond the lake basin, in the form of severe environmental, ecological, and socioeconomic problems, including erosion, dust storms, degraded water quality and associated human health issues, and local economic downturn catalyzed by collapsing fisheries (Dokhuvny and Stulina, 2001; Cai, et. al.2003).

2.2. The Kissimmee River Channelization

The channelization of the Lower Kissimmee River, Florida, for flood control purposes illustrates the undesirable effects of human interference with natural ecosystems in the absence of a comprehensive understanding of the major physical and ecological aspects of watersheds. The Kissimmee River Flood Control project was initiated in 1954, following public pressure in the aftermath of a series of hurricanes that caused extensive damage to properties and loss of human life (Shen et al., 1994). To provide protection against flooding, the river was channelized, and its flow regulated by canals and water control structures, which transformed the river-floodplain to a series of deep impoundments. Completed in 1971, the project dramatically changed the hydrologic characteristics of the river basin as the wetlands and historical water-level fluctuations were eliminated (Toth, 1993; Shen et. al, 1994; Whalen et al., 2002).



(a) 1960 (b) 1990

(c) 2008

Figure 1. The Aral Sea over time. (Wikimedia Commons, available at http://commons.wikimedia.org/wiki/File:Aral_Sea.gif)

(a) (b)

Figure 2. Channelized Kissimmee River (a) versus restored system (b) (from Wikimedia Commons (a), http://commons.wikimedia.org/wiki/File:Kissimmee_River_canal_section.jpg, and South Florida Water Management District (b), http://www.sfwmd.gov/portal/page/portal/pg_grp_sfwmd_ watershed/pg_sfwmd_watershed_kissimmee)

Ecosystem degradation followed in the form of dramatic changes of the flora and fauna throughout the project area. As the basin was no longer inundated by flood waters, plant and animal species associated with terrestrial habitats took hold. Modified flow regimes resulted in encroachment of vegetation into the canal, which in turn substantially lowered dissolved oxygen concentrations in the water. Subsequently, fish species tolerant of low oxygen levels emerged and quickly replaced the sport fish species commonly found in the past. Soon after completion of the river channelization, the Kissimmee River restoration project was undertaken (Figure 2) to restore over 43 continuous miles of river and 40 square miles of associated floodplain wetlands, and to save over 320 fish and wildlife species at a cost of about US$ 500 (Whalen et al., 2002; Layzer, 2008).

2.3. Zayandeh-Rud Watershed

The Zayandeh-Rud River basin is another example of watershed mismanagement, where a poor understanding of the interrelationships of different water resources management subsystems has resulted in prescribing temporary engineering solutions which fail in the long-run (Madani and Marino, 2009). In semi-arid central Iran the Zayandeh-Rud River has been utilized for centuries as the primary supply source for agricultural, industrial, and domestic water uses, mainly in the Isfahan Province, the second largest industrial region in Iran. The river currently provides water for over 4.5 million people and over 260,000 hectares of farmland. Increasing water use has exceeded naturally available surface water supplies, and subsequent groundwater mining has caused groundwater tables to decline. To handle ongoing water shortages in the face of growing demands, resulting from increased immigration, river basin water managers have adopted trans-basin water transfer as their main policy, which has doubled the potentially available water in the basin through several water diversion projects. However, soon after completion of each trans-basin water diversion project, the additional water is fully allocated (Figure 3), without due regard for drought management and environmental conservation. Not surprisingly, Gav-khuni marshland, an environmental asset internationally recognized under the Convention on Wetlands (1971), now receives less than half of the average historical river flow needed to sustain the natural marshland ecosystem (Salemi et. al., 2000; Madani and Marino, 2009).

(a) (b)

Figure 3. Zayandeh-Rud River near Khaju Bridge (from Madani, 2005 (a) and Foltz, 2002 (b))

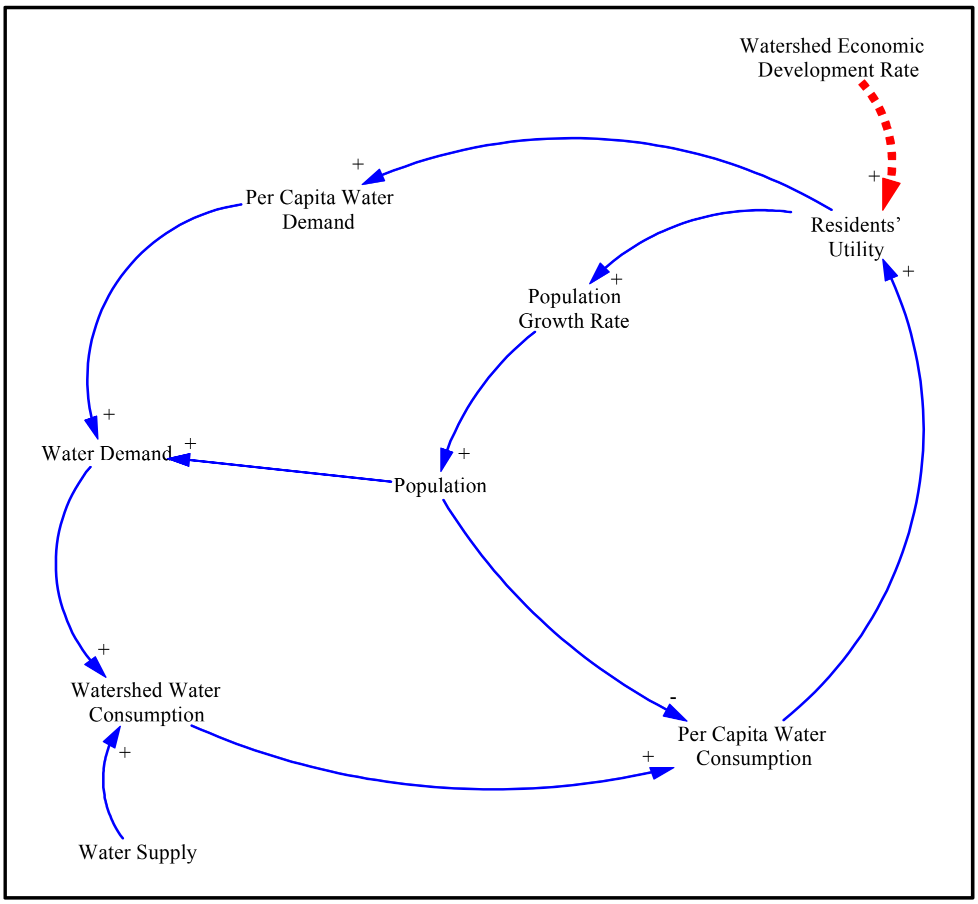


Figure 4. Zayandeh-Rud socio-economic subsystem with watershed economic development as the main driver (adopted from Madani and Marino (2009))

Without recognizing the source of water shortages in the Zayandeh-Rud watershed, planners have continuously tried to overcome the problem by curing the symptoms rather than addressing the root problem. While the problem may be solved by controlling groundwater withdrawal and water demand through water markets and by increasing water prices, the government continues to provide highly subsidized water to farmers who use more than 90 percent of the water in the basin. Although increasing population and demand, driven by the growing economy, are the main causes of water shortages in this basin, the policy makers have attempted to solve the problem simply by providing more water to the residents. This short-sighted engineering solution has supported development and made the region more attractive to immigrants, resulting in growing water demand and shortages (Figure 4) (Madani and Marino, 2009), which in turn may lead to dramatic environmental and economic losses in the long run.

The above examples portray how a lack of understanding of watershed subsystems can cause environmental disasters as well as socioeconomic problems affecting humans' well-being. In many cases, watershed modeling is needed to create a framework for analysis of the system's behavior under natural variability and human alteration before making changes to watersheds or water management policies. Well-designed and efficiently implemented watershed models provide effective tools for integrated studies of the major physical, socioeconomic, and political aspects of watersheds at a reasonable cost and within a specified timeframe.

3. Chronological Synthesis of Watershed Modeling

For decades, water resources professionals have been developing and applying models to address watershed problems, yet watershed models are still evolving in terms of approach, application, and ability to provide users with a comprehensive and reliable understanding of problems. Watershed modeling efforts before 1960 were aimed mostly at quantitative representation of individual hydrologic processes (see reviews by Singh and Woolhiser, 2002; Chen 2004; Crawford and Burges, 2004). Various components of the hydrologic cycle, such as surface runoff, infiltration, groundwater flow, and evapotranspiration, were modeled separately (Singh and Woolhiser, 2002), but a lack of data and computing capability hindered more integrated analysis (Freeze and Harlan, 1969; Chen 2004).

Watershed modeling was revolutionized after the advent of computers in the 1960s. Development of the Stanford Watershed Model in 1966 (Crawford and Linsley, 1966) initiated a prolific era of modeling efforts that incorporated snowmelt runoff, stream-aquifer interaction, reservoir and channel flow routing, and water quality into watershed models such as Hydrologic Simulation Program FORTRAN (Johanson et al., 1984; Singh and Woolhiser, 2002) and HEC rainfall runoff and river hydraulics models (USACE, 1989).

Early attempts to develop an integrated approach to planning and design of water resources systems can be traced back to 1955 when the Harvard Water Program brought together a group of professors with engineering, economics, and political science backgrounds to integrate economic theory and engineering practice through a multidisciplinary environment (Maass et al., 1962; Reuss, 2003). In the late 1960s and early 1970s, economic water demand curves were used to establish a conceptual framework for regional scale integrated water management models that maximize the net benefits of water allocation (Harou et al., 2009). Following these early economic modeling efforts, many researchers have contributed to build hydroeconomic models of watershed systems by linking hydrological, hydrogeological, hydraulic, and biogeochemical processes to economic principles to facilitate integrated planning and management of watersheds (Brouwer and Hofkes, 2008). However, watershed planning and management decisions may not only rely on economic and hydrologic aspects of the system. In 1990s and 2000s, a plethora of research has been carried out on hydroeconomic models (Heinz et al., 2007; Brouwer and Hofkes, 2008; Harou et al., 2009), along with consideration of social and political aspects of watershed systems (Griffin, 1999; Korfmacher, 2001; Beck et al., 2002; Bagheri, 2006; Madani and Marino, 2009), which demonstrates a trend towards more holistic modeling approaches.

Since the time of development of Stanford Watershed model, the computational capacity to run sophisticated models has continuously increased at an overwhelming rate (Singh and Frevert, 2006). Over the same period, watershed models have evolved from purely engineering/economic models to more integrated tools that are capable of addressing various planning, design, and management problems with a desired level of detail. Growing computational capabilities, together with integration of data processing and management tools such as Geographic Information Systems (GIS) and data-base management systems with the watershed models (Singh and Woolhiser, 2002), has allowed for detailed spatial and temporal analyses of watershed systems. Likewise, great technological advances in remote sensing, satellites, and radar applications, combined with GIS techniques and an enhanced ability to perform field measurements, have facilitated more spatially distributed modeling of watersheds (Kite and Pietroniro, 1996; Fortin et al., 2001; Chen 2004). Figure 5 schematically illustrates how watershed models are becoming more comprehensive and sophisticated thanks to increasing data processing capabilities and adoption of an interdisciplinary approach to address a wide spectrum of problems ranging from strategic level decisions to development of design alternatives.

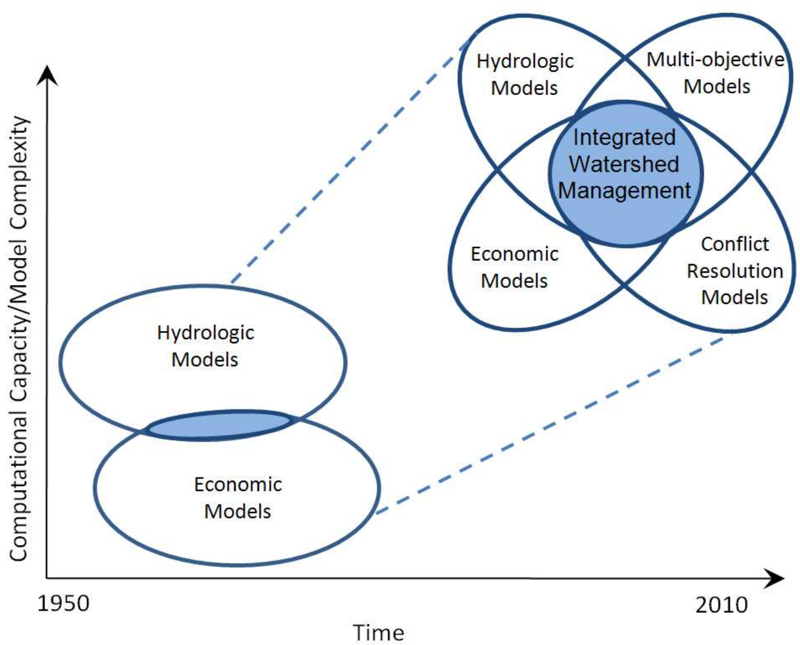


Figure 5. Integrated watershed modeling evolution over time

4. WATERSHED MODELING METHODS AND APPROACHES

Watershed modeling methods and approaches have been categorized in different ways according to the types of problems they address and their method of finding a preferred solution. When categorized according to their solution method, models are classified either as simulation or optimization models. While there is a clear distinction between these two, as will be described below, many watershed studies involve a combination of simulation and optimization to analyze watershed systems and develop effective management policies. Alternatively, watershed models may be classified according to their scope and purpose into the following categories: engineering-based watershed process models, hydroeconomic models, multi-criteria (multi-objective) decision making models, and conflict resolution models. Each of these categories of models is briefly described below.

4.1. Modeling Methods: Simulation and Optimization

Depending upon the type and nature of the watershed planning and management problem being addressed, modelers have used either simulation or optimization models, or in some cases both, as the primary methods to study and analyze watersheds. There are some key differences in the philosophy of these two modeling methods, and proper understanding of these differences is crucial to selection and application of the appropriate model.

Simulation models take physical parameters and engineered designs, or management plans, as inputs and generate detailed predictions of outcomes. Simulation is widely applied in the detailed design phase of projects for quantitative performance and impact analysis of a limited number of alternative designs. The method is suitable for sensitivity (or "what if") analysis under a number of scenarios of interest. For example, a modeler may wish to use a simulation model to evaluate the performance of alternative designs under drought, normal, and flood scenarios. If performance of each alternative is unacceptable, new alternatives must be developed and evaluated. Engineering-based simulation is thus considered as an alternative-focused method in which the modeler intends to reach the best possible alternative design or quantitative representation of natural systems through a trial and error process (Makowski et. al., 1996; Garbrecht, 2006).

Optimization methods are geared towards creating alternatives based on selecting values for decision variables that provide the best value of an objective function, subject to a set of mathematical constraints (equations or limits that need to be satisfied in order for a particular alternative to be feasible). Understandably, expressing operational objectives and constraints in a mathematical form that can be solved by a computer often requires simplification of physical and socioeconomic relationships. Some advantages of optimization models are that they can help to screen a large number of potential alternatives, generate new alternatives that otherwise may have been overlooked, and provide an intuitive means of trade-off analysis. Also, optimization results need to be interpreted carefully, as the "optimal" outcomes may be overly optimistic and not achievable in practice. Table 1 compares some main aspects of simulation and optimization models.

Optimization and simulation modeling are not mutually exclusive. In many studies, they are used in complementary fashion to support decision making. For example, following the preliminary screening of alternatives, feasible alternatives generated by optimization can be simulated for detailed analysis and impact prediction (Loucks and Van Beek 2005).

Table 1. Simulation vs. optimization methods

	Simulation Model	**Optimization Model**
Suitable for	"What if" questions	"What's best" questions
Development effort	Low	High
Computational efficiency	High	Low
Transparency/ acceptability to the stakeholders	High	Low

4.2. Modeling Approaches: Scope and Problems Addressed

4.2.1. Watershed process models

Watershed process simulation models are used for quantitative analysis, or prediction, of natural processes occurring at the watershed scale, to understand watersheds' natural behavior or their response to human- engineered alterations (Singh and Woolhiser, 2002). The structure of watershed process models varies depending upon modeling objectives, but in general they are built using a series of mathematical equations that describe the components of hydrologic or biogeochemical cycles, such as surface water hydrology, hydrogeology, soil chemistry, and limnological processes, to name a few. Presently, there exists a large number of generalized watershed simulation models that include, among others, rainfall-runoff processes, river hydraulics, groundwater hydraulics, and water quality processes (Wurbs, 1998). By focusing on natural processes, these models are often able to provide a detailed representation of one or more watershed subsystems.

Engineering-based watershed process models are frequently applied in watershed planning and management to help raise the decision makers' awareness of technical nuances of proposed design alternatives, and predict the potential impacts of projects prior to their implementation. Table 2 presents some example applications of physically-based watershed process models for watershed management and decision making. Watershed process models have been used in a wide range of studies, including rainfall-runoff prediction, flood mitigation design, water supply development, safety assessment of water infrastructure, land use planning, irrigation planning, hydropower operations, and surface and groundwater quality protection.

Table 2. Example applications of physically based watershed process models.

Problem(s) addressed	Objective(s)	Modeling approach	Location	Citation
Anthropogenic alteration of hydrologic behavior of a subalpine watershed	Quantifying the role of watershed management in hydrologic changes	Yearly basin-scale water balance simulation	Colorado, USA	Leaf and Brink (1973)
Lake-watershed acidification due to transport of airborne pollutants and acid rains	Providing a quantitative link between atmospheric deposition and lake water chemistry	Simulation of, hydrological, ecological, chemical, and limnological processes	New York, USA	Chen et al, (1982)
Frequent inundation of a community by backwater, tidal, and headwater flooding	Evaluating impacts of proposed levee extension project on hydrologic and hydrodynamic conditions	Hydrologic and hydrodynamic Modeling	Louisiana, USA	Wang (1987)
Safety assessment of an existing high-hazard dam	Determining adequacy of dam freeboard and spillway capacity	Hydrologic modeling and flood routing	Ontario, Canada	Lee (1996)
Runoff induced erosion and pollutant mobilization	Understanding hydrologic and morphologic behavior of grassed areas	Runoff and sediment transport simulation	Serbia	Deletic (2001)
Water quality degradation due to runoff and sediment transport	Addressing non-point source pollution issues	Watershed process modeling, phosphorus loading estimation	Iowa, USA	Abaci and Papanicolaou (2007)
Water quality deterioration driven by agricultural practices	Evaluating the effects of landscape characteristics (e.g. land use, soil type, and slope) on surface water quality	Watershed process simulation	Taiwan	Chang et al. (2008)
Intensified wetland soil quality degradation due to large-scale agricultural reclamation	Evaluating soil quality variation in top layers of wetland soils	Soil quality analysis using fuzzy synthetic evaluation	China	Wang (2009)
Water overabundance and scarcity; flash flooding followed by periods of low stream flows	Evaluating impacts of meteorological events, land use change and urban development on stream flows	Watershed process simulation	Mexico	Habarth and Barkdoll (2009)
Extensive development and consequent aggravation of floods in urban watersheds	Demonstrating effectiveness of distributed detention reservoirs and reforestation of slope areas in flood mitigation	Watershed process simulation	Brazil	Miguez et al. (2009)

4.2.2. Hydroeconomic watershed models

Apart from its life-sustaining role, water has economic value for various in-stream and off-stream uses such as domestic use, agriculture, industry, transportation, recreation, waste assimilation, and ecosystem maintenance (Gibbons, 1986). While physically-based watershed process models can capture the natural hydrologic behavior of watersheds, they have traditionally neglected the economic aspect of watershed modeling. However, water scarcity manifested by drought-induced economic downturn and intensified by growing demands for water necessitates consideration of appropriate economic factors in a robust watershed modeling framework to devise economically justifiable watershed management plans. Hydroeconomic models, often based on optimization methods, possess the advantage of facilitating economic studies by maximizing or minimizing some specified economic objective function subject to a series of constraints.

Harou et al. (2009) describe hydroeconomic watershed models as solution-oriented tools that foster formulation of new strategies to promote water-use efficiency and transparency of decision making, thus contributing to integrated water resources management. However, maximizing the economic value of water use serves as the only driver of decisions in hydroeconomic models as economic valuation of many social, political and environmental objectives remains difficult. Integrated modeling of watershed-scale hydrological, environmental, and economic aspects of water use often requires simplified representation of natural processes (Heinz et al., 2007). Thus, water resources management decisions which are solely based on hydroeconomic models may not be comprehensive and a holistic model and approach are required for integrated water resources management.

Table 3 summarizes some typical applications of hydroeconomic watershed models. Hydroeconomic models have been applied to analyze water resources management practices and potential economic and environmental impacts, to address trade-offs and interactions among various stakeholder groups, to evaluate long term drought management and flood mitigation plans, to improve water resources operation policies and strategies, to suggest climate change adaptation strategies, and to improve water quality and quantity for ecosystems.

Table 3. Example applications of hydroeconomic models

Problem(s) addressed	Objective(s)	Modeling approach	Location	Citation
Economic inefficiency, groundwater misallocation due to nonexistent groundwater control mechanisms	Deriving approximate decision rules for ground water storage control	Hydroeconomic optimization	California, USA	Burt (1964)
Uncontrolled spatial and temporal use of groundwater and associated economic inefficiency	Determining socially optimal groundwater allocation schedule for agricultural and municipal demands	Hydroeconomic optimization	California, USA	Noel et al., (1980)
Multitude of user groups and inevitable trade-offs in the Missouri River multi-reservoir system	Developing economically-based reservoir operating rules	Hydroeconomic optimization Optimization-Simulation	USA	Lund and Ferreira (1996)
Ecological degradation due to water diversions	Evaluating potential benefits of enhancing in stream flows and fish habitat	Integration of economic, fish population, physical habitat, and water allocation models	Colorado, USA	Hickey and Diaz (1999)
Environmental degradation due to unsustainable water allocation	Understanding environmental impacts of water markets	Hydroeconomic optimization	Queensland, Australia	Tisdell (2001)
Drying of the Aral Sea due to unsustainable irrigation withdrawals	Addressing stakeholder conflicts and associated socioeconomic and environmental issues	Hydrologic, agronomic, and economic simulation and optimization modeling	Aral Sea Region, Central Asia	Cai et al. (2003)
Managing a complex multipurpose (agriculture, flood control, hydropower, urban water supply, environmental uses) water system	Developing a statewide water resources management model, policy impact assessment, identifying best management policies	Hydroeconomic optimization	California, U.S.A.	Draper et al. (2003); Jenkins et al. (2004); Tanaka et al. (2008)
Increasing competition among major demand sectors and degraded water quality	Optimizing water allocation, reservoir operation, and irrigation scheduling	Hydroeconomic simulation and optimization	Chile	Cai et al. (2006)
Inefficient water management and system operation	Maximizing economic benefits by conjunctive use of surface and groundwater	Hyrdoeconomic framework, watershed process simulation and economic analyses	Spain	Velázquez et al. (2006)
Ecological and socioeconomic impacts of growing demand and water shortage	Evaluation of hydrologic and economic trade-off among water uses, regions, and drought control programs	Hydroeconomic optimization of water allocation	USA	Ward et al. (2006)

Table 3. (Continued)

Problem(s) addressed	Objective(s)	Modeling approach	Location	Citation
Climate variability impacts on navigation, water supply, and hydroelectric power generation at Panama Canal	Improving operating policies and analyzing potential benefits of capacity expansion	Hydroeconomic optimization modeling	Panama	Watkins and Moser (2006)
Increasing flood risk due to climate change and urban development in a levee protected floodplain	Investigating optimal long-term floodplain protection decisions	Hydroeconomic optimization model	California, USA	Zhu et al. (2007)
Climate change, population growth and land use effects on California's water resources system	Identifying adaptation strategies and estimating economic losses	Hydroeconomic optimization	California, USA	Medellin-Azuara et al. (2008)
Water scarcity and degraded water quality	Improving water quantity and quality at a range of scales through water and land management changes	Hydroeconomic modeling, ecological and socio- economic assessment, watershed process simulation	Germany	Volk et al. (2008)
Climate change effects on hydropower generation in California	Estimating of revenue changes and exploring the vulnerability of the system	Hydroeconomic optimization	California, USA	Madani and Lund (2009; in press)
Drought effects on land use, farm profits, and agricultural employment	Investigating the economic behavior of farmers, agricultural production, and drought-induced hydrologic changes derived from agricultural activity	Hydrologic simulation and hydroeconomic optimization	Brazil	Maneta et al., (2009)

4.2.3. Multi-objective decision making models

Watershed planning and management decisions almost always consider multiple goals, many of which are conflicting. Often it is impossible to aggregate the goals into a single criterion or performance measure in the alternative ranking and selection process (Makowski et. al. 1996). Thus, multi-criteria (or multi-objective) decision support methods are widely applied for water policy planning and evaluation, strategic watershed planning and management, and infrastructure development (Hajkowicz and Collins 2007). In the context of optimization modeling, these methods seek to generate solutions that are "non-dominated," meaning that performance with respect to one objective cannot be improved without decreasing performance with respect to another objective. For example, reservoir operators need to consider the trade-off between water supply and flood mitigation benefits, as increasing the reliability of meeting a target supply (i.e., storing more water in a reservoir) would impose additional flood risk (Figure 6). By using optimization, all dominated solutions may be screened out, and the non-dominated solutions evaluated for trade-offs, allowing the decision maker to focus on a smaller set of potentially preferred alternatives. Multi-criteria decision making (MCDM) methods such as ELECTRE, Compromise Programming, and the Analytic Hierarchy Process provide a framework for evaluating trade-offs and selecting a preferred alternative from among a set of potential solutions to a problem (Hajkowicz and Collins 2007). For watershed systems, MCDM methods may consider quantitative and qualitative criteria such as engineering standards and expected performance, environmental integrity, investment and operating costs, equity, and aesthetics (Hipel 1992).

Multiple criteria analysis techniques have aided water resources practitioners to select decision or design alternatives in such areas as river basin planning and development, water resources development, land use management, groundwater/surface water allocation, watershed restoration, and water resources quality (Table 4).

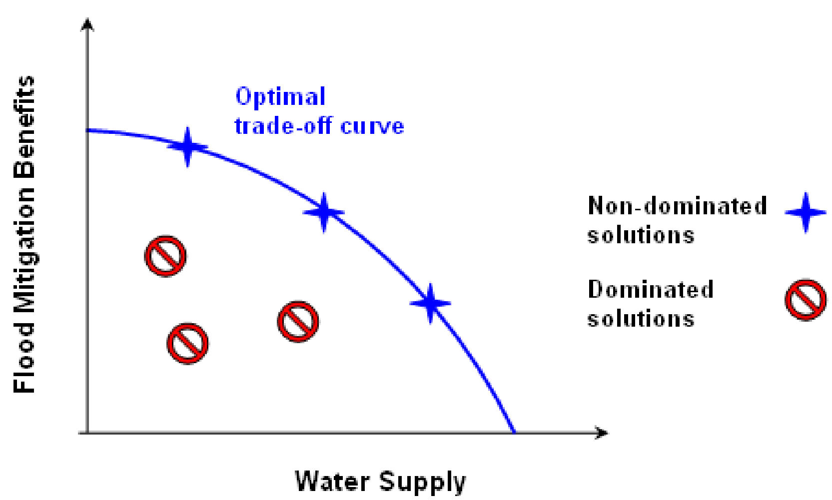


Figure 6. Two-objective trade-off between water supply and flood mitigation benefits

Table 4. Example applications of multi-criteria (multi-objective) decision making.

Problem(s) addressed	Objective(s)	Modeling approach	Location	Citation
Optimal, multiobjective planning and development at river basin scale	Combining cost-effectiveness analysis with compromise programming to design a water resources system	Multiobjective optimization	Hungary	Duckstein (1979)
Impact of various water development strategies on an urbanized area	Examining the applicability of multiple approaches in river basin planning	Multi-objective decision making	Arizona, USA	Gershon and Duckstein (1983)
Inefficient reservoir system operation	Finding a preferred policy for multi-objective reservoir system operation	Multi-objective modeling	South Korea	Ko et al. (1992)
Conflicts over water resources allocation, water quality, unclear water rights	Proposing management alternatives for compromise over water allocation	Compromise programming and ELECTRE III, Multiobjective analysis,	USA	Bella et al. (1996)
Water quality impairments in a river basin	Evaluating trade-offs among costs and water quality standards for several constituents	Multi-objective optimization	Slovakia	Makowski et al. (1996)
Conflicts related to land use and ecological impacts due to agricultural and urbanization activities	Developing a decision support system to for planning and prioritizing watershed restoration projects	Multiobjective decision making combined with GIS	Oregon, USA	Lamy et al. (2002)
Water quality impairments in a river basin	Developing a water quality management plan	Multi-objective decision making	Taiwan	Lee and Chang (2005)
Nitrate contamination of groundwater	Determining sustainable nitrogen loadings and proposing protection alternatives	Multi-criteria decision analysis, groundwater quality simulation	Washington, USA	Almasri and Kaluarachchi (2005)
Ecological and socioeconomic deterioration of the Aral Sea region	Supporting policy formulation process for mitigation plans	Multi-objective water allocation modeling combined with integrated simulation modeling	Aral Sea Region, Central Asia	Schlüter et al. (2006)
Water scarcity and long-term impacts of transbasin water diversions	Analyzing interactions among various drivers of water shortages and recommend sustainable strategies	System dynamics simulation	Iran	Madani and Marino (2009)
Inefficient irrigation water management strategies	Improving irrigation water allocation with respect to socioeconomic and environmental objectives	Multi-criteria decision making	Greece	Latinopoulos (2009)

4.2.4. Conflict resolution models

The multitude of watershed planning and management objectives inevitably leads to conflicts among watershed stakeholders, or interest groups. In many cases, however, different stakeholder groups share common interests (e.g., a homeowner along a river may be primarily concerned about flood risk reduction but may also value the riverine ecosystem), or they may be able to reach compromise agreements (e.g., development of one portion of the floodplain may be offset by enhancing wetlands in another portion). Conflict resolution models essentially seek to promote compromise through holistic understanding of technical, socioeconomic, political, and environmental aspects of the problem (Lund and Palmer, 1997). Conflict resolution models have served as flexible tools for quantitative and qualitative analysis of watershed systems to suggest, given the circumstances, what would happen to the system based on detectable trends, stakeholders' interests, concerns, and behavior. Unlike the traditional "win-lose" or "zero-sum" conflict resolution approach, water resources conflict resolution models seek to lead the parties involved in the conflict towards a "win-win" situation or a " positive-sum", socially feasible solution (Nandalal and Simonovic, 2003).

Conventionally, most multi-criteria decision making models tend to transform multi-objective problems to a single composite objective (e.g. economic benefit, environmental integrity, social welfare), assuming that stakeholders will perfectly cooperate to reach the system's optimal solution (Madani, 2010). However, such an assumption may result in unrealistic results. Therefore, other conflict resolution models should be considered, such as game theory models which are capable of generating a more realistic simulation of stakeholders' and decision makers' behaviors by accounting for their concern to maximize their own benefit (Madani, 2010). By creating a platform for collaborative modeling and constructive negotiation, conflict resolution models can enhance stakeholders' and decision makers' understanding of the problem and aid in the definition of solution objectives and constraints. Collaborative modeling can facilitate the development of feasible alternatives, as well as the evaluation of alternatives' performance and impacts. Proper use of conflict resolution models has been found to increase technical confidence in the solution agreed upon (Lund and Palmer, 1997).

Various conflict resolution techniques have been used to help resolve conflicts such as those arising over water resources allocation, apportionment, and threats to environmental integrity due to human alteration. Table 5 summarizes some applications of conflict resolution models in watershed planning and management.

Table 5. Example applications of conflict resolution models

Problem(s) addressed	Objective(s)	Modeling approach	Location	Citation
Flooding of Ganges and Brahmaputra rivers and associated loss of life and property damage	Developing a rational flood control plan and investigating cooperation opportunities	Conflict resolution, game theory	India, Pakistan	Rogers (1969)
Allocation of costs of a water resource development project among 18 municipalities	Developing a fair allocation of costs among the parties.	Cooperative game theory	Sweden	Young et al. (1980)
Wastewater reuse and cooperation in water use for irrigation	Developing a fair and efficient allocation of benefits	Cooperative game theory	Israel	Dinar et al. (1992)
Conflict over a transboundary water resource	Study the conflict and provide decision advice and a deeper understanding of the conflict under consideration, Providing strategic insights into the conflict	Graph model for conflict resolution, game theory	Northern America; Middle East; Africa	Hipel et al. (2002); Madani and Hipel (2007); Elimam et al. (2008)
Conflict over water allocation in dry periods	Demonstrating the role of negotiation among stakeholders	Cognitive mapping	Italy	Giordano et al. (2005)
Water use conflicts due to competition of users in a water-scarce watershed	Improving water regulation policies for irrigation and power generation	Watershed process simulation	Nepal	Pokharel (2005)
Conflict over sharing the Caspian Sea and its resources after collapse of the Soviet Union	Identifying the most likely outcome of the conflict and proposing some possible allocations.	Fallback bargaining, Social choice rules, bankruptcy procedures, descriptive modeling	Caspian Sea Countries	Sheikhmohammady and Madani (2008a), (2008b), (2008c)
Upstream versus downstream conflict following construction of two multi-purpose dams	Identifying and evaluating acceptable management alternatives, facilitating sustainable water resource management	Multi-criteria decision making, conflict resolution modeling	South Korea	Ryu et al. (2009)
Climate change effects on Federal Regulatory Commission (FERC) hydropower relicensing process	Investigating the effects of climate change on cooperation among the hydropower generators and the environmentalists	Conflict resolution, cooperative game theory	USA	Madani (2009)

5. FUTURE DIRECTIONS IN WATERSHED MODELING

To date, watershed modelers have been able to capture the key hydrological behaviors of many watershed systems. Despite the complexity and uncertainty of various watershed processes, many engineering-based models have been successfully calibrated, verified, and applied by decision makers. Our ability to model hydrologic processes with greater accuracy, and at finer spatial and temporal resolution, will continue to improve with increased use of remotely sensed data (e.g., satellite observations), increased computational capacity, and improvements in GIS and database management systems. However, computational capacity, data availability, and model complexity will not increase at the same rate, and thus there is always a danger of two types of "modeling error": (1) Developing an overly complex model that cannot be properly calibrated and verified using available data, or (2) Developing a model that fails to make proper use of available, high-quality data.

While future watershed process models may suffer from either of these two kinds of error, it is likely that integrated watershed management models will suffer primarily from the first kind. Determining "the best" set of watershed management practices is complicated by a host of regional and global-scale socioeconomic, political, climatic, and biogeochemical factors. Even setting the global-scale issues aside, our ability to account for and predict dynamic, interactive socioeconomic and policy aspects of watershed systems is still questionable. To do this reliably, fundamental advances in economics and other social sciences may be required. However, even as planning and management model complexity outpaces observational data, proper recognition and accounting of uncertainty in predicted socioeconomic and policy outcomes will be critical to determining areas where improved understanding of human systems is most needed. Increased experience with multi-criteria and conflict resolution models, and analysis and documentation of this experience, will also further understanding of the role of models in watershed planning, management, and decision making.

6. CONCLUSION

Natural and anthropogenic processes within watersheds are complex, dynamic, and spatially variable. Previous experiences of unsuccessful or unsustainable watershed planning and management practices manifest how a lack of understanding of watershed subsystems can cause environmental disasters as well as socioeconomic problems affecting humans' well-being. Watershed modeling has become a commonplace tool for water resources system design, planning, and management at an affordable cost and within a reasonable timeframe. The computer revolution in the mid 1960's and continuous growth in computational capacities, along with other advances in data collection and management, has allowed watershed models to evolve from describing only physical processes to describing the interaction of social, economic, and environmental systems objectives in support of decision making. The gradual shift from merely employing engineering-based simulation models to applying integrated hydroeconomic models, and more recently multi-criteria/multi-objective decision making and conflict resolution models, is an indicator of promising changes in the traditional paradigm for the application of watershed models. More holistic understanding of watershed systems, consideration of multiple stakeholder values, objectives and behavior, and improved abilities to predict and plan for future impacts are likely to lead to more sustainable watershed planning and management decisions.

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