6

SWIM Paper

Modeling Water Resources Management at the Basin Level: Review and Future Directions

Daene C. McKinney, Ximing Cai
Mark W. Rosegrant, Claudia Ringler
and
Christopher A. Scott

SWIM

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System-Wide Initiative on Water Management

SWIM Papers

In an environment of growing scarcity and competition for water, increasing the productivity of water lies at the heart of the CGIAR goals of increasing agricultural productivity, protecting the environment, and alleviating poverty.

TAC designated IWMI, the lead CGIAR institute for research on irrigation and water management, as the convening center for the System-Wide Initiative on Water Management (SWIM). Improving water management requires dealing with a range of policy, institutional, and technical issues. For many of these issues to be addressed, no single center has the range of expertise required. IWMI focuses on the management of water at the system or basin level while the commodity centers are concerned with water at the farm and field plot levels. IFPRI focuses on policy issues related to water. As the NARS are becoming increasingly involved in water management issues related to crop production, there is strong complementarity between their work and many of the CGIAR centers that encourages strong collaborative research ties among CGIAR centers, NARS, and NGOs.

The initial publications in this series cover state-of-the-art and methodology papers that assisted the identification of the research and methodology gaps in the priority project areas of SWIM. The later papers will report on results of SWIM studies, including inter-sectoral water allocation in river basins, productivity of water, improved water utilization and on-farm water use efficiency, and multiple uses of water for agriculture. The papers are published and distributed both in hard copy and electronically. They may be copied freely and cited with due acknowledgment.

Randolph Barker
SWIM Coordinator

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The International Irrigation Management Institute, one of sixteen centers supported by the Consultative Group on International Agricultural Research (CGIAR), was incorporated by an Act of Parliament in Sri Lanka. The Act is currently under amendment to read as International Water Management Institute (IWMI).

Contents

CGIAR Centers

CIAT	Centro Internacional de Agricultura Tropical
CIFOR	Center for International Forestry Research
CIMMYT	Centro Internacional de Mejoramiento de Maize y Trigo
CIP	Centro Internacional de la Papa
ICARDA	International Center for Agricultural Research in the Dry Areas
ICLARM	International Center for Living Aquatic Resources Management
ICRAF	International Centre for Research in Agroforestry
ICRISAT	International Crops Research Institute for the Semi-Arid Tropics
IFPRI	International Food Policy Research Institute
IIMI	International Irrigation Management Institute
IITA	International Institute of Tropical Agriculture
ILRI	International Livestock Research Institute
IPGRI	International Plant Genetic Resources Institute
IRRI	International Rice Research Institute
ISNAR	International Service for National Agricultural Research
WARDA	West Africa Rice Development Association

Abstract

The world is facing severe and growing challenges in maintaining water quality and meeting the rapidly growing demand for water resources. In addition, water used for irrigation, the largest use of water in most developing countries, will likely have to be diverted increasingly to meet the needs of urban areas and industry whilst remaining a prime engine of agricultural growth. Finally, environmental and other in-stream water demands become more important as economies develop.

The river basin has been acknowledged to be the appropriate unit of analysis to address these challenges facing water resources management; and modeling at this scale can provide essential information for policy makers in their decisions on allocation of resources. This paper reviews the state of the art of modeling approaches to integrated water resources management at the river basin scale, with particular focus on the potential of coupled economic-hydrologic models, and concludes with directions for future modeling exercises.

Executive Summary

This review paper addresses the most common river basin management tools, including water resources management modeling at the subsystem and river-basin levels. At the subsystem level, the tools of reservoir operation, groundwater management, conjunctive surface water and groundwater management as well as irrigation and drainage management are reviewed in the context of integrated water quantity and quality management.

Optimal reservoir system operations– often the principal infrastructure component of water resources management systems– have long featured in the tool kits of water engineers. The modeling of optimal groundwater quality and quantity management has proven more elusive due to the inherent complexity of aquifers, the host of hydrologic uncertainties, the simultaneous use of groundwater as water supply and waste dilution, its complementary use to stochastic surface supplies, and its common property resource status.

The conjunctive management of surface water and groundwater can increase the efficiency, reliability, and cost-effectiveness of water use in a stream-aquifer system. Several simulation/optimization procedures have been developed to study conjunctive use problems. Longer-term problems often address water quality issues in conjunctive use management, especially (ground)water quality and salinity changes in irrigation systems.

Irrigation and drainage management in the context of water quality and quantity management focuses on a combination of the dynamics of soil moisture and salt movement in the root zone, management strategies, and economic incentives. Short-term models estimate the optimal combination of water quantity and quality for 1 year or a single irrigation season. Long-term models account for the effects of salt accumulation in the soil profile over time. Finally, extended long-term models also take the salt accumulation in the groundwater into account. Whereas dynamic programming has been used to solve short- and long-run models, interactive simulation and optimization are generally necessary to solve extended long-run models. Runoff irrigation modeling presents an additional tool to supplement conventional irrigation modeling.

A river basin system is made up of water source components, in-stream and off-stream demand components, and intermediate (treatment and recycling) components. The river basin is characterized not only by natural and physical processes but also by physical projects and management policies. The essential relations within each component and the interrelations between these components in the basin can be considered in an integrated modeling framework. Basin-scale models can be traced back to the 1920s, but major breakthroughs were not achieved until the 1960s; and only since the 1980s when user-friendly PCs were introduced have basin models acquired further diffusion. The two principal approaches to river basin modeling are simulation– to simulate water resources behavior based on a set of rules governing water allocations and infrastructure operation; and optimization– to optimize allocations based on an objective function and accompanying constraints.

Simulation is the preferred technique to assess water resources system responses to extreme, nonequilibrium conditions, like droughts, and thereby to identify the system components most prone to failure, or to evaluate system performance relative to a set of sustainability criteria over a long time period, like climate change, or to rapidly changing priority demands,

like accelerated municipal growth. The range of river basin simulation models can be classified into flow simulation models, quality simulation models, water rights simulation models, and comprehensive simulation models.

Optimization models are based on an objective function and constraints and can include social value systems in the allocation of water resources. They can be hydrology-inferred or based on economic criteria of optimal water allocation. However, optimization models usually contain a simulation component to characterize the hydrologic regime, and are thus usually referred to as integrated simulation and optimization models. A wide range of models of this type has been developed, often including a basin or subbasin, but mostly focusing on one sectoral water user or a few of them.

Important economic concepts that need to be examined through integrated economic-hydrologic river basin modeling include transaction costs, agricultural productivity effects of allocation mechanisms, inter-sectoral water allocations, environmental impacts of allocations, and property rights in water for different allocation mechanisms. Water/crop production functions for the irrigated water uses– evapotranspiration models, simulation models, estimated models, and hybrid models– are a necessary component for economic approaches in river basin management. Mathematical programming models are used to allow for the joint choice of cropping patterns, water application levels, and water application technologies. Nonagricultural water uses include domestic, industrial, environmental, and in-stream demands. Due to the unique characteristics of water and the absence of markets in most cases, the value of water has to be often inferred, through market-based valuation techniques and nonmarket techniques. Market-based valuation techniques include the sales comparison technique, the least-cost alternative technique, and the extraction cost method. Nonmarket techniques include techniques of revealed preference and contingent valuation methods.

Combined hydrologic and economic models are best equipped to assess water management and policy issues in a river basin setting. Integrated economic-hydrologic models can be classified into those with a compartment modeling approach and those with a holistic approach. Under the compartment approach there is a loose connection between the economic and hydrologic components, that is, only output data are usually transferred between the components. The various (sub) models can be very complex but the analysis is often difficult due to the loose connection between the components. Under the holistic approach, there is one single unit with both components tightly connected to a consistent model, and an integrated analytical framework is provided. However, the hydrologic side is often considerably simplified due to model-solving complexities. The most outstanding models using the holistic modeling approach are the Colorado River Basin Models CRS/CRM/CRIM. GIS-based decision support systems can support both modeling and analysis of river basins. Whereas GIS offer a spatial representation of water resources systems, decision support systems are interactive programs, which embed traditional water resources simulation and optimization models. Several studies have successfully applied GIS-based decision support systems in river basin models. The approaches range from loose coupling, the transfer of data between GIS and numerical models, to tight coupling, in which GIS and the models share the same database. The tightest of couplings consists of an integrated system, in which modeling and data are embedded in a single manipulation framework.

It is at the basin level that hydrologic, agronomic, and economic relationships can be integrated into a comprehensive modeling framework and, as a result, policy instruments, which are designed to make more rational economic use of water resources, are likely to be applied at this level. Improved basin-scale modeling of water policy options will be an important direction for water management research in the immediate future. Efficient and comprehensive analytical tools are needed to make the rational water allocation decisions necessary to achieve sustainable water use strategies for many river basins. The future direction for modeling will lie in GIS-based decision support systems that integrate economic, agronomic, institutional, and hydrologic components.

Ultimately, such an integrated hydrologic-agronomic-economic-institutional model, which is built on an integral river basin network, should include the following processes or relationships:

- integrated water quantity and water quality regulation

- spatial and temporal externalities resulting from the distribution over time and across locations of water supply and demand

- crop acreage and crop production functions incorporating both water application and salinity

- effects of uncertainty and risk concerning both water supply and demand

- appropriate representation of water demands from all water-using sectors for analysis of inter-sectoral water allocation policies

- economic incentives for salinity and pollution control, water conservation, and irrigation system improvement

Modeling Water Resources Management at the Basin Level: Review and Future Directions

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Introduction

Background and Rationale

The world is facing severe and growing challenges in maintaining water quality and meeting the rapidly growing demand for water resources. New sources of water are increasingly expensive to exploit, limiting the potential for expansion of new water supplies. Water used for irrigation, the largest use of water in most developing countries, will likely have to be diverted to meet the needs of urban areas and industry whilst remaining a prime engine of agricultural growth. Waterlogging, salinization, groundwater mining, and water pollution are putting increasing pressure on land and water quality. Pollution of water from industrial waste, poorly treated sewage, and runoff of agricultural chemicals, combined with poor household and community sanitary conditions, is a major contributor to disease and malnutrition. In many areas, water is available to users at no cost or at a heavily subsidized price. Thus neither water managers nor water users have incentives to conserve water, so water is overused and wasted instead of being treated as a scarce resource.

New strategies for water development and management are urgently needed to avert severe national, regional, and local water scarcities that could depress agricultural production, cause rationing of water to the household and industrial sectors, damage the environment, and escalate water-related health problems. A large share of water to meet new demands must come from water saved from existing uses through a comprehensive reform of water policy. Such reform will not be easy, because both long-standing practice and cultural and religious beliefs have treated water as a free good and because entrenched interests benefit from the existing system of subsidies and administered allocations of water. Furthermore, the gains from demand management will be more difficult to achieve than is suggested by much of the literature.

Integrated management must be the primary approach to addressing sustainable water resources, both for national and international water systems. It is at the basin level that water allocation decisions have wider economic implications. As a result, policy instruments designed to make more rational economic use of water resources are likely to be applied at this level. The river basin has long been acknowledged as the appropriate unit of analysis for water resources management and has also been named by the United Nations Conference on Environment and Development (UNCED) as the unit of analysis for integrated water resources management in Agenda 21, chapter 18. The activities suggested in chapter 18 include the "development of interactive databases, forecasting models, economic planning models and methods for water management and planning," and the "optimization of water resources allocation under physical and socioeconomic constraints" (UNCED 1998).

In some river basins, efficiency gains from existing systems may prove to be limited, because whole-basin water use efficiencies are already high as a result of reuse and recycling of drainage water, even though individual water users may be inefficient. Overall irrigation efficiencies (the product of irrigation system efficiency and field application efficiency) in developing countries are low, ranging from 25–40 percent for India, Mexico, Pakistan, the Philippines, and Thailand to 40–45 percent in Malaysia and Morocco, compared with 50–60 percent in Israel, Japan, and Taiwan (Rosegrant and Shetty 1994). These low water use efficiencies are often cited as evidence that very large savings in water use can be obtained. However, unmeasured downstream recovery of "waste" drainage water and recharge and extractions of groundwater can result in actual basin-wide efficiencies substantially greater than the nominal values for particular systems (see, for example, Keller 1992). Water losses at the river basin level are

- Losses of water vapor to the atmosphere through evaporation from surfaces and by evapotranspiration of plants.
- Flows of water to salt sinks, including oceans, inland seas, and saline aquifers.
- Pollution of surface water and groundwater by salts or toxic elements so that water becomes unusable (Seckler 1996).
- The economic sink, which includes water that drains from the system and seeps or percolates into groundwater or other freshwater sinks, but which is not economically feasible to recover because the cost of reuse is too high (Rosegrant 1997).

The task of demand management is to generate both physical savings of water and economic savings by increasing output per unit of evaporative loss of water, increasing the utilization of water before it reaches salt sinks, reducing water pollution, reducing the loss of water to the economic sink, and by restoring the existing water in the economic sink to use. It is unclear empirically how large each of these potential water savings is, and important research remains to be done on this issue. Definite estimates of the potential for improving system performance by increasing effective water supply will require basin-specific analyses (Rosegrant 1997).

Clearly, the allocation of water resources in river basins is a critical issue. The sustainability of future economic growth and environmental health depends on it. However, river basins are inherently complex systems with many interdependent components. Efficient and comprehensive analytical tools are needed to make the rational water allocation decisions necessary to achieve sustainable water use strategies for many river basins. The objective of this paper is to assess the potential of coupled economic-hydrologic models to address critical issues related to increasing water demand and the resulting inter-sectoral competition over water in the context of past modeling experience in both the economic and hydrologic fields. The paper presents a state-of-the-art review of integrated, basin-scale water resources management modeling and suggests future directions for basin modeling for water management and policy analysis.

This section reviews some concepts and classifications useful for river basin water resources management. Section 2 introduces the application of mathematical models in integrated water quantity and quality management. It reviews river basin management tools, including water resources management modeling at the subsystem and at the river basin levels. At the subsystem level, the tools of reservoir operation, groundwater management, conjunctive management of surface water and groundwater as well as management of irrigation and drainage are reviewed. At the river basin level, a short overview of the evolution of basin-scale models is presented. Then simulation, optimization, and integrated simulation and optimization models are discussed. Section 3 discusses economic approaches in water resources allocation, in particular, production functions with water and nonagricultural functions of water demand. In Section 4, past experience with the integration of economic and hydrologic models is examined, with emphasis on compartment and holistic modeling approaches. The use of Geographic Information Systems (GIS) in water resources management modeling is discussed in Section 5 as well as the research advances and future potential of GIS. Based on the review in Sections 1–5, future directions in modeling are presented in the concluding section. Comprehensive information support and system integration have improved basin-scale water resources management modeling, but few comprehensive modeling efforts have been attempted. Moreover, even fewer models have been applied successfully for policy analysis. The overview shows that additional research and refinement in modeling will be necessary and that GIS-based decision support systems, which integrate economic, agronomic, institutional, and hydrologic components, appear to be the most promising direction for future research.

River Basin Concepts for Water Resources Management

Integrated water resources management

Water resources management includes both structural interventions and nonstructural rules and policies. In the traditional structural or engineering approach, water resources management is seen as the design of suitable physical works under the criteria of safety, workability, durability, and economy. The physical works include short-term, operation and maintenance activities with existing structures and long-term investments in new structures. However, since the middle of this century, the nonstructural approach has become attractive to water resources managers and researchers. Hydrologists have been researching optimal operating rules of hydrologic systems; economists have been applying methods of optimization in water allocation; and sociologists have been examining community behavior and processes relating to the formation and support of agencies making decisions about water management. These institutional directives, economic/financial incentives, and hydrologic system operating rules have greatly modified the traditional engineering approach. This review paper focuses on the nonstructural aspect of water management.

The interdisciplinary nature of water problems requires new methods to integrate the technical, economic, environmental, social, and legal aspects into a coherent framework. Water resources development and management should incorporate environmental, economic, and social considerations based on the principles of sustainability. They should include the requirements of all users as well as those relating to the prevention and mitigation of water-related hazards, and constitute an integral part of the socioeconomic development planning process (Young, Dooge, and Rodda 1994). The objective function is an essential instrument to reflect the host of rules, principles, and constraints in water resources management in a modeling framework. In many cases, several objectives (economic efficiency, social well-being, environmental sustainability, etc.) have to be dealt with simultaneously. Some broad concepts applicable to water resources management can be found in US Water Resources Council 1983 and OECD 1985.

Some of these criteria have been applied in multiple objective decision analysis methods, a traditional approach to solve water resources management problems (see Chankong and Haimes 1983). However, economic objective functions can be combined more easily with hydrologic models than environmental or social well-being criteria that are often difficult to express in quantitative terms. The traditional way is to scale all criteria to nondimensional values, while specifying the same range for all criteria so that the objectives are comparable in the objective function. Weights must be assigned to each of the criteria to indicate their relative importance (see McKinney and Cai 1996, for an example). However, the selection of weights is often arbitrary (Young 1996). In addition, the inherent hydrologic uncertainties should be incorporated into the analytical framework. Watkins and McKinney (1997) and Watkins (1997) have done a recent review of this topic.

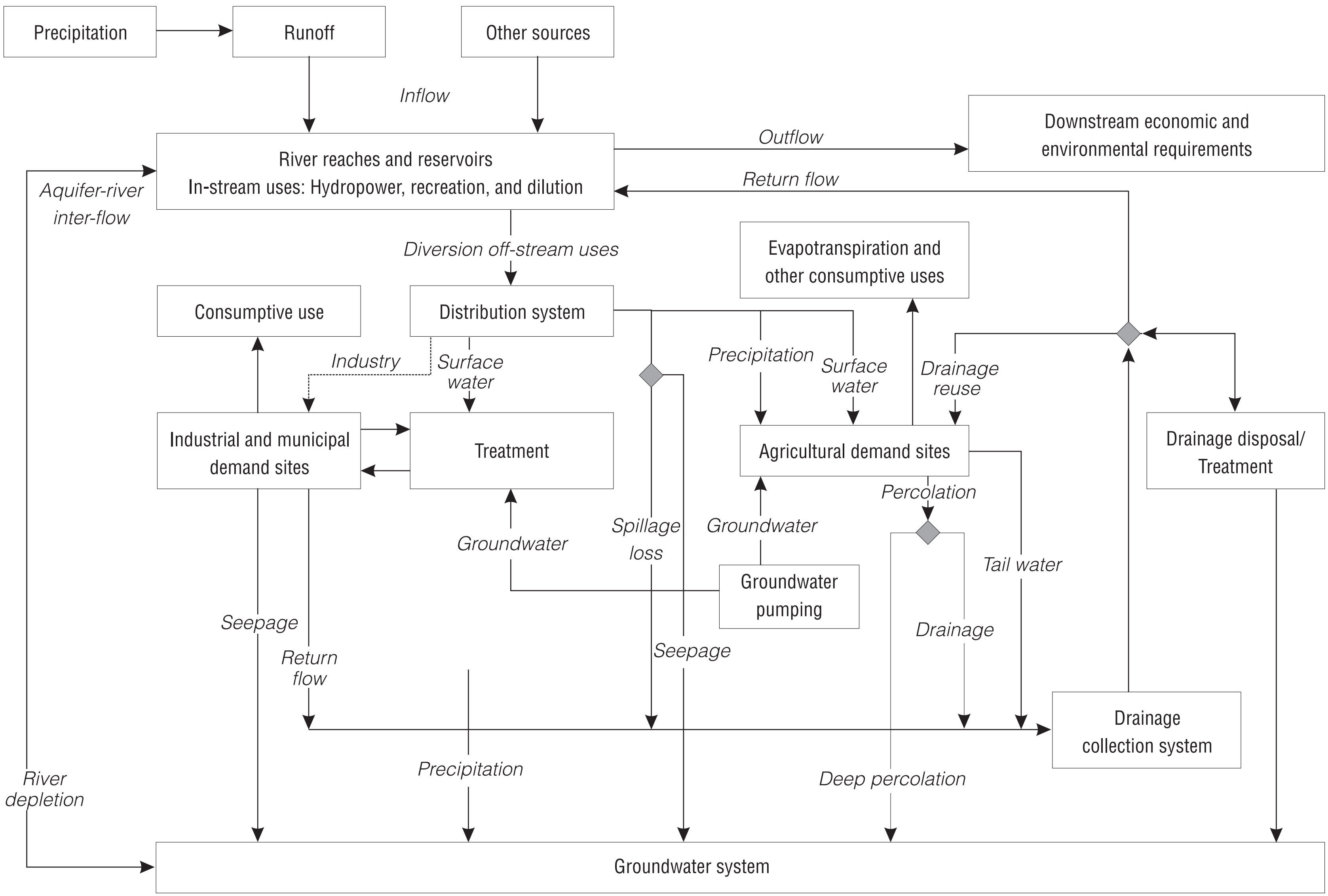
These principles have also been embraced, at least *de jure,* by most international bodies, as can be seen in the Dublin Statement of the International Conference on Water and the Environment and UNCED, both in 1992. In addition, the World Bank has shifted away from past approaches that tended to center on supply strategies to focus more on measures of demand management, which address the incentives and mechanisms that promote water conservation and efficient use of water (Serageldin 1995). Finally, newly founded international fora, like the Global Water Partnership and the World Water Council, emphasize integrated water resources management; the former supporting "integrated water resources management programmes by collaboration, at their request, with governments and existing networks and by forging new collaborative arrangements," (GWP 1998) and the latter seeking to "develop do-able approaches to the potentially very complex problem of meeting multiple demands for water by multiple inter-linked resources" (WWC 1998).

River basin systems

A river basin system is made up of three components: (1) source components such as rivers, canals, reservoirs, and aquifers; (2) demand components off-stream (irrigation fields, industrial plants, and cities) and in-stream (hydropower, recreation, environment); and (3) intermediate components such as treatment plants and water reuse and recycling facilities. Figure 1 shows a schematic diagram of the components of a river basin system, which includes the water supply system (groundwater and surface water), the delivery system (canal network), the water users system (agricultural, municipal, and industrial), and the drainage collection system (surface and subsurface). The atmosphere forms the river basin's upper bound, and mass and energy exchange through this boundary determines the hydrologic characteristics within the basin. However, the state of the basin (for example reservoir and aquifer storage, and water quality) and the physical processes within the basin (for example stream flow, evapotranspiration, infiltration and percolation) are also characterized by human actions, including impoundment, diversion, irrigation, drainage, and discharges from urban areas. Therefore, water resources management modeling of a river basin system should include not only natural and physical processes, but artificial "hardware" (physical projects) and "software" (management policies) as well. An ideal, complete management model also needs some sub-model of human behavior in response to policy initiatives. This may be as simple as a price elasticity of demand coefficient or something more complex (such as a model of the irrigators' simultaneous choice of optimal water use, crops, and water application technology). The essential relations within each component and the interrelations between these components in the river basin can be considered in an integrated modeling framework.

In this review, we focus on the management issues of river basin systems, and generally assume that the water supply starts from rivers, reservoirs, and aquifers. Inflows to these entities can be calculated through precipitation-runoff models. However, this is beyond the purpose of this review. The effects of climate and hydrologic

FIGURE 1.
Schematic representation of river basin processes (adapted from Daza and Peralta 1993).



fluctuation on water supply can be included in water management models through prescription of climatic and hydrologic scenarios.

Figure 2 presents a framework for river basin management modeling, including relationships and decision items at various levels. Water can be used for in-stream purposes, including hydropower generation, recreation, waste dilution, as well as off-stream purposes that are differentiated into agricultural water uses and municipal and industrial (M&I) water uses. The objective of the modeling is to maximize the socioeconomic benefits of the river basin area, which not only include positive contributions from the economic value of M&I water use, profit from irrigation, and benefits from in-stream water uses, but also entail environmental damage due to the M&I waste discharge, irrigation drainage, and potential negative impacts on in-stream uses. The top control for the system is assumed to be the institutional directives like water rights, and economic incentives such as the water price, the crop price, and penalty taxes on waste discharge and irrigation drainage, which constrain or induce hydrologic system operations and decisions within both M&I and agricultural demand sites. Water uses are competitive between in-stream water uses, M&I water supply, and irrigation water supply, under prescribed institutional rules, organizational structures, and economic incentives. The hydrologic system interacts with the M&I water use system, the irrigation and drainage system, and the in-stream water use system. The operation of the hydrologic system is driven by the water use systems and, at the same time, these water use systems are constrained by the hydrologic system.

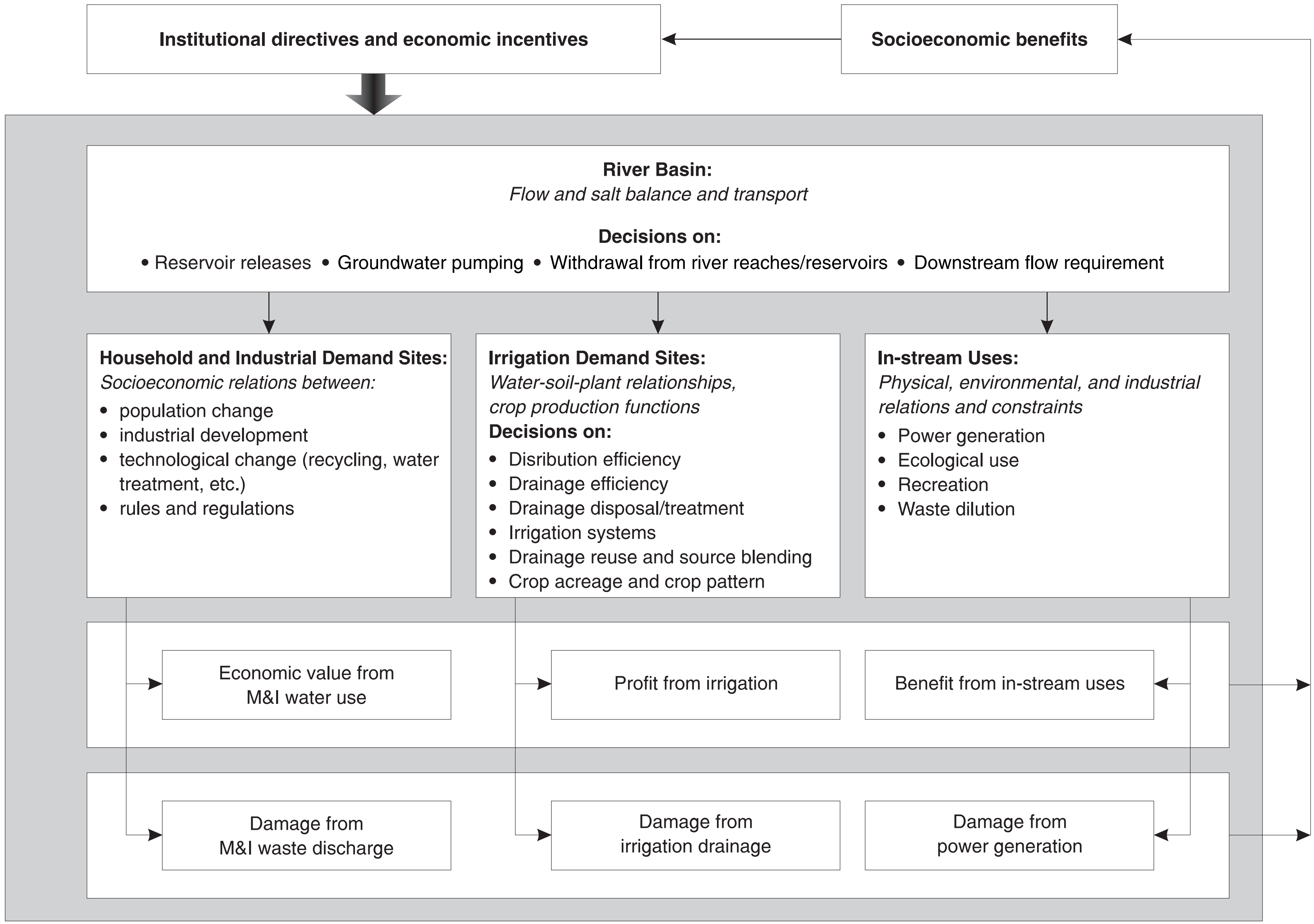
The management of water quantity and quality in a basin is based on the operation of reservoir systems, aquifers, and conjunctive surface water and groundwater systems. The difference between the work at this scale and the study of separate entities lies in the characteristics of the river basin scale: flow distribution and constituent transport are considered for the entire basin, including streams and rivers, diversion canals and drainage collectors, reservoirs and aquifers, and water use sites (for example, irrigated fields, and M&I areas). The connections between sources and water use sites and between upstream and downstream water use sites are important considerations, which are handled by including return flows in the model. The regulation of spatially distributed flow sources, pollutants, and water demands have to be considered and mathematical models built based on an integral river basin network.

Integrated Water Quantity and Quality Management

Introduction

The single-objective, single-purpose, and single-facility project approach to solve water resources allocation problems that was common in many developed-country water planning agencies in the past has gradually been replaced by multi-objective, multipurpose, and multi-facility solutions at the river basin level. Water quality standards used to be specified prior to the modeling, and these standards were then used as the "driving force" to determine water supply and waste loading. Instead, nowadays, water quality and environmental impacts, as well as economic benefits, are being considered in a more comprehensive fashion. Water quantity and quality objectives are more and more integrated into an analytical framework based on the physical interrelationships between flow and constituents, as well as on the related socioeconomic and environmental policies.

FIGURE 2.
Framework for river basin management modeling.



Integrated water quantity and quality management has been applied in reservoir operation, groundwater use, conjunctive use of surface water and groundwater, irrigation and drainage management, and the system operation at the river basin level. The objectives of water quality management include

- satisfying water quality standards for water supply
- downstream water quality control, including low-flow augmentation
- groundwater quality maintenance
- salinity control in agricultural fields and return flows

Mathematical models have been extensively applied to the analysis and decision processes of water quantity and quality management. These models include simulation models, optimization models, and combined simulation and optimization models.

Representations of hydrologic processes at scales ranging from the soil profile to the cropped field and to the irrigated command area are important precursors to understanding and describing the processes at the river basin scale. However, water allocation decisions have wider economic implications at the basin level. Thus, effective policy instruments for optimal water allocations should be designed and applied at this level of analysis. In the following, a brief overview of water resources management modeling at the subbasin level will be presented, followed by a review of model development at the river basin scale.

Water Resources Management Modeling at the Subsystem Level

Introduction

In this section, a review of mathematical models for integrated water quantity and quality management below the basin scale is presented, including reservoir operation, groundwater management, conjunctive use of surface water and groundwater, and irrigation and drainage management. The focus will be on model development for both water quantity and quality regulation. Additional reviews on these topics are given by Loucks (1996) and Yeh (1985) for reservoir operation, Yeh (1996) for groundwater systems, and Replogle, Clemmens, and Jensen (1996) for irrigation systems. System analysis techniques, including linear programming, nonlinear programming, dynamic programming, stochastic techniques, and multi-objective analysis have been applied extensively to solve the water resources management problems in the models reviewed below.

Reservoir operation

Through the mid-1980s, river basin models focused on the functioning of the principal infrastructure component of most water resources management systems, the reservoir. Several studies have been carried out to develop optimum operating policies for reservoir systems considering both water quantity and quality as objectives. These studies can be classified into two groups: downstream water quality control without considering water quality in reservoirs (Jaworski, Weber, and Deininger 1970; Loucks and Jacoby 1972; Ikebuchi, Takasao, and Kojiri 1982; Orlob and Simonovic 1982; Martin 1983; Kojiri 1987; Harboe 1992; Ko, Fontane, and Labadie 1992) and water quality control considering both reservoirs and downstream flows (Ikebuchi and Kojiri 1992; Dandy and Crawley 1992; Nandalal and Bogardi 1995).

Ikebuchi, Takasao, and Kojiri (1982) study the real-time operation of a reservoir system with the objective of turbidity control, as well as low flow and flood control. The objective during high-flow periods was to control the peak release, and the objective during low-flow periods was to maximize the lowest flow and to minimize peak turbidity by regulating reservoir releases. The authors assume inflow turbidity to the reservoirs to be a power function of flow and complete mixing within the reservoirs. They use dynamic programming to identify optimum releases. Kojiri (1987) extends this work to consider multi-objective tradeoffs between low-flow discharge and turbidity in the released water.

Harboe (1992) applies 6 multi-objective decision making techniques to identify optimal operating rules for reservoir systems. The techniques include the constraint method, compromise programming, goal programming, the Tchebycheff approach (max-min), Consensus, and ELECTRE I and II. As objectives he uses hydropower production, water supply, flood control, low-flow augmentation, reliability, recreation, and water quality. In a two-step approach, the author first generates a number of alternatives by using optimization and/or simulation techniques. In the second step, objective weights are determined. The final decisions are based on the multi-objective decision-making techniques. Harboe uses several examples to show tradeoffs, such as low-flow versus flood control, low-flow and recreation versus water quality.

Buras (1972) includes water quality modeling within reservoirs in his study of the release policy and salt control of a reservoir used in conjunction with an aquifer with the help of stochastic dynamic programming. Dandy and Tan (1987) examine the development of an operating policy for the Encounter Bay district in South Australia. The authors use three sources of water for their simulation model, each of them with differing supply costs and differing water quality characteristics (namely color, turbidity, and salinity). Based on the model, the authors evaluate various supply policies in a multi-objective framework. However, optimal or near-optimal solutions cannot always be found due to the lack of an optimization mechanism. Dandy and Crawley (1992) study the development of an operating policy for a reservoir system in which water quality is modeled and considered explicitly in the operating policy. They use an optimization model to determine the releases of the reservoir system, and a simulation model to account for the salinity in the reservoir system. The two models are run interactively until convergence is achieved. The modeling framework involves several assumptions: (1) complete mixing occurs in each reservoir, and (2) the rates of inflow, outflow, and spill for each reservoir are constant during each time period. The authors apply this framework to the operation of a headwork system with high salt concentration. More recently, Nandalal and Bogardi (1995) combined water quantity and quality equations into a single optimization model that can include both inflow and release control. The authors use the incremental dynamic programming technique to determine the reservoir operational policy.

Management of groundwater

Integrated quantity and quality management. Groundwater sources are the main water supply for many agricultural and urban areas. Much research effort has been directed toward maintaining a water supply of adequate quantity and quality for various agricultural and municipal purposes. The underlying management problem here is the use of aquifers for both water supply and treatment (or disposal) (Willis 1979; Gorelick 1983).

The simulation of groundwater quantity and quality resources is based on the equations of groundwater flow and contaminant advection-dispersion in saturated media (Gorelick 1983). The application of finite difference and finite element methods to these equations has permitted the numerical modeling of complex, real world systems. The simulation of groundwater behavior is typically incorporated into a management framework following two methods: the *embedding method* and the *response matrix approach* (Willis 1978). In the former, finite difference or finite element approximations of the governing groundwater flow and contaminant transport equations, treated as part of the constraint set, are directly embedded in a mathematical programming model; in the latter, a response matrix is included in the management model. The response matrix, in which each unit describes the influence of a pulse stimulus upon hydraulic heads or concentrations at points of interest through a system, is developed by using an external groundwater simulation model.

Gorelick (1983) finds that a lot of research has focused on solving water quality management models with known groundwater velocity fields in integrated groundwater quantity and quality approaches. When groundwater velocity fields are unknown they should be determined conjunctively in a water quality management model. In these cases, the contaminant transport equation and the groundwater flow equation must be solved simultaneously. However, nonlinearities arise as a result of products of unknown concentrations and unknown velocity components, which occur in advective and dispersive transport terms. The most tight connection of water quantity and quality aspects exists in these nonlinear models. Wagner (1995) provides a recent review of advances in groundwater management models.

Other groundwater management models with integrated quantity and quality considerations include work by Willis (1979) who studies the problems associated with the injection of wastewater into an aquifer system conjunctively managed for supply and quality; by Willis and Roger (1984) who formulate a multi-objective optimization problem allocating groundwater over a series of planning periods for water supply and plume management; and by Shafike, Duckstein, and Maddock III (1992) who discuss groundwater management using a multi-criteria decision method (MCDM) to determine pumping location and rates for trading off freshwater supply, waste contaminants, and total pumping cost in a hypothetical confined aquifer. Jones, Willis, and Yeh (1987), for example, develop a generalized Direct Dynamic Programming (DDP) algorithm to solve large-sacle, nonlinear groundwater-optimization models.

The economics of groundwater quantity and quality management. Compared to other aspects of subbasin modeling, groundwater management has attracted perhaps the most attention from economists. It is therefore useful to briefly review the approaches to economic-hydrologic modeling used for groundwater management. A more comprehensive review of economic valuation techniques is provided in Section 3. Modeling of groundwater has included valuation of groundwater storage in arid and semiarid areas with intensive water demand, efficient water use and recharge, incentives to induce optimal actions, institutional directives, and associated equity consequences.

Tsur and Graham-Tomasi (1991) study the buffer value of groundwater in a case where groundwater was used to mitigate fluctuations of a stochastic surface water source for irrigation. The authors find a positive buffer value of a significant magnitude, confirmed through numerical studies. They assume a deterministic recharge rate independent from the amount of surface water.

Both management policies and hydrologic uncertainties affect benefits of groundwater management. Feinerman and Knapp (1983) examine the benefits from groundwater management by using a systematic analysis method. They analyze the magnitude of the benefits, their sensitivity to various parameters, and related welfare effects on groundwater use. They find that water users gain under quotas but suffer heavy losses under taxes, and that benefits are extremely sensitive to the interest rate and water demand curve. This study by Feinenman and Knapp (1983) assumes a single-cell aquifer, and does not take the considerable complexity of the aquifer into account. It also does not address water quality issues.

As a common property resource, groundwater is likely to be used inefficiently, as withdrawals are likely to be excessive (above natural and artificial recharge levels). The optimal rate at which a groundwater source should be used, or should be recharged is important to both private and public decision-making units. Burt (1964) uses a functional equation, based on a dynamic programming formulation to derive approximate decision rules (pumping rate over time period) for resources use, which he then applies to groundwater storage control. He derives a price expression based on optimal conditions, and uses it to implement the storage control. The author claims that if the two conditions of (1) identical production functions for all producers, and (2) commodities produced in small enough quantities relative to total market are met, then the pricing method provides a basis for rationing water optimally.

Brown and Deacon (1972) analyze the optimal economic use of an aquifer over time under conditions of economic growth, inequality of groundwater withdrawal and consumption, and availability of surface water and artificial recharge. The authors examine, among others, the relation between optimal lift levels and pumping taxes. They find that groundwater users with different rates of return flow should pay different pumping tax rates and that the introduction of either surface water or artificial replenishment raises the water table and lowers the pumping tax. The authors also make an explicit distinction between water quantity and quality and derive the value of an aquifer as a natural water quality treatment facility.

Groundwater is generally used complementary to stochastic surface supplies. The risk associated with surface water uncertainty makes optimal groundwater management more complicated. Knapp and Olson (1996) find that optimal decision rules generally increase hydraulic heads and decrease surface flows, and that optimal management benefits from groundwater management are relatively small. However, they conclude that optimal management reduces the variability of returns; this benefit might be larger under risk aversion.

Institutional rules that are applied to prevent excess withdrawal, control pollution, and maintain equity are especially important for common property resources management, like groundwater management. Provencher and Burt (1994) compare the social welfare of pumping groundwater under central (optimal) control to that obtained under a private property rights regime in which firms are granted tradable permits. They conclude that

- The private property rights regime is usually inefficient due to its cost and externalities.
- The private property rights regime may, however, yield greater welfare than central control because markets for permits provide opportunities for risk management, which are not available under central control.
- The difference between the value of groundwater under central control and the private property rights regime may be sufficiently small in practice for the private property rights regime to remain a viable alternative to central control.

Young, Daubert, and Morel-Seytoux (1986) develop a simulation model of a hydrologic-legal-farmer decision system and employ the model to analyze several institutional alternatives for managing a stream-aquifer system in which groundwater pumping adversely affects river water flow. They model two types of individual firm decisions: irrigation scheduling in the short run, and the choice of crop pattern and irrigated land in the intermediate run. Their objective is to maximize net income subject to available production technologies, a given set of crop and input prices, and a given level of water supply. The authors conclude that a quasi-market "augmentation plan," flexible enough to produce a more efficient allocation under a wide range of water supply conditions, is successful from an economic perspective. They also claim that their model represents an inexpensive way to analyze the allocative and distributive consequence of alternative rules. Only a few other studies that include economics embrace the complexity of groundwater systems. Instead, economists often treat resources use problems, such as shortages, pollution, conflicts over entitlements to use water, and environmental degradation from an economic point of view, without sufficiently integrating the physical/technical side. A review of integrated economic-hydrologic models at the river basin scale is presented in Section 4.

Conjunctive management of surface water and groundwater

The literature includes numerous studies on the conjunctive management of surface water and groundwater resources. Conjunctive management can increase the efficiency, reliability, and cost-effectiveness of water use in a stream-aquifer system (Yeh 1996). Gorelick (1983) and Willis and Yeh (1987) provide an excellent review of integrated water quantity and quality management modeling in aquifer and stream-aquifer systems.

Young and Bredehoeft (1972) use a detailed hydrologic simulation model in conjunction with a (deterministic) net benefit optimization model to address a conjunctive use problem in Colorado, USA, and– for the case study considered– they conclude that centrally controlled groundwater development would probably lead to greater net benefits than unregulated development.

Helweg and Labadie (1977) develop a water allocation mechanism for a river subbasin, with emphasis on cost-effective salinity management. The basic idea for this mechanisms is to accelerate the downstream transport of salts by encouraging application of pumped water downstream. The authors develop a management algorithm, combining an optimization model and a detailed quantity-quality simulation model to implement this technique. The optimization model generates least-cost alternatives for distributing water over the subbasin. These alternatives are subsequently examined in a simulation model framework for their effectiveness in controlling the salt balance. The two models are solved separately, period by period, over the time horizon. The authors apply the management algorithm to the Bonsall subbasin of the San Luis Rey river basin.

Louie, Yeh, and Hsu (1984) study a multi-objective simulation/optimization procedure for unified basin-wide water resources management, considering three major water management problems: (1) water supply allocation; (2) water quality control; and (3) prevention of undesirable groundwater overdraft. The authors implement the optimization procedure solving several optimization and simulation models interactively. The three management problems are solved separately, based on three corresponding optimization and simulation models. The optimization model for water quality control is solved in combination with a groundwater quantity-and-quality model or a river flow-and-mass transport model through the influence coefficient method (Becker and Yeh 1972). After the three optimization models are solved, payoff tables are created, and the original multiple objective problem is converted into a constrained problem including the three water management issues. Finally, the authors solve the constrained problem for non-inferior solutions. The procedure is applied to a small test problem.

There has been considerable interest in evaluating long-term trends of groundwater quality within irrigated stream-aquifer systems by studying the relationship between agricultural practices and water quality variations in these systems. These models consider groundwater flow, solute transport, stream-aquifer interflow, water use decisions, and agronomic relationships between crop production, the depth of applied irrigation water, and water quality.

Konikow and Person (1985) apply the solute transport model of Konikow and Bredehoeft

(1974) to evaluate long-term salinity changes and their relation to irrigation practices within the stream-aquifer system on an 11-mile reach of the Arkansas river valley. Lefkoff and Gorelick (1990a) construct a model to examine the effect of crop-mixing strategies on long-term profits in an irrigated, saline stream-aquifer system. Their model contains three components: (1) an economic component to model water use decisions to maximize annual profits; (2) a hydrologic component to simulate salt transport by employing regression equations that predict changes in groundwater salinity as a function of hydrologic conditions; and (3) an agronomic component to approximate changes in corn and alfalfa production in response to the depth and salinity of irrigation applications. This economic-hydrologic-agronomic model represents a comprehensive approach for water resources management at the irrigation system level.

Daza and Peralta (1993), arguing that the inclusion of deep percolation reduction could be a key factor in developing strategies for groundwater quantity and quality conservation, develop a conjunctive water management model for an irrigated area. The model components include the description of several subsystems in the study area: the water supply system (surface water and groundwater), the delivery system (canal network), the water users system (agricultural and nonagricultural), and the drainage collection system (surface and subsurface drainage). The model structure consists of a transient multilayer groundwater hydraulic simulation/optimization approach and incorporates the irrigation technology explicitly. Irrigation inflow is a decision variable, and deep percolation and runoff losses from irrigation are state variables.

Peralta, Kowalski, and Cantiller (1988), Lefkoff and Gorelick (1990a), and Peralta et al. (1990) apply simulation-optimization models to determine an optimal irrigation strategy that maximizes crop yield while preventing groundwater contamination. Of these studies, the most detailed of the vadose zone processes involves modeling a single-layer root zone. Salt concentration is calculated based on a volume balance basis, without a spatially detailed description of vertical system dynamics. The work by Musharrafieh et al. (1995) is an exception, because it uses a one-dimensional simulation/optimization model including implicit finite-difference forms of the unsaturated water flow equation (Richard's equation), the advection-diffusion solute transport equation, functions describing the hydraulic properties of a medium, a root extraction function, and other constraints. The model uses a large discretization in time and relies on a cycle prediction and correction-type approach to eliminate the inaccuracy that would otherwise result from the coarse discretization.

Billib et al. (1995) develop a multi-step modeling approach for a multi-objective decision problem of a conjunctive use system, simultaneously considering irrigation, hydropower production, and water supply, as well as water quality maintenance. The system includes a surface water reservoir with a hydropower plant, a groundwater reservoir, an artificial recharge area, and pumping fields as well as a channel distribution system for five irrigation areas. The authors apply a three-step procedure to combine the short-term (hydrologic year) decision with the multiyear analysis. First, they analyze a long-term time series for groundwater prediction; second, they use the Incremental Dynamic Solving Technique (IDST), linked with groundwater flow and solute transport simulation, to select short-term preferred decisions; finally they simulate long-term groundwater flow to analyze the impact of the yearly operation rules on the long-term behavior of the quality parameters.

More recently, Wong, Sun, and Yeh (1997) presented a methodology to determine multi-period optimal conjunctive use of surface water and groundwater with water quality constraints. The methodology includes three models: a two-dimensional groundwater flow model, a two-dimensional contaminant transport model, and a nonlinear optimization model. The flow and contaminant transport models are solved separately. Based on the results, the authors establish a drawdown limit and a concentration limit in the optimization model to determine the water supply from the surface water source, the groundwater source, and an imported source in each time period.

Management of irrigation and drainage

Introduction. Due to increasing water scarcity and worsening water quality conditions, greater attention has been given to integrated water quantity and quality management in irrigated agriculture. Inappropriate irrigation is often responsible for (1) highly saline drainage returning to surface water and groundwater systems, (2) long-term salt accumulation in soils (Hanks and Andersen 1979), and (3) waterlogging and other negative environmental effects, like water pollution from inadequate pest management or soil erosion. Irrigation planning should take into account both irrigation purposes and salinity control (Yaron et al. 1980).

The physical basis for integrated water quantity and quality management includes the dynamics of soil moisture and salt movement in the root zone, which is generally described by Richard's equation. These physical relations, combined with management strategies and economic incentives, have been extensively studied since the 1970s. Some detailed simulation models that approximate these physical relationships in irrigated fields have been developed (for example, Skaggs 1980; Parsons, Skaggs, and Doty 1991). The models can be classified according to their time frame (Yaron et al. 1980): short-term, long-term, and extended long-term models.

Short-term models. A short-term model is confined to 1 year or a single irrigation season. These models typically deal with the initial salinity of the soil profile; and analyze the optimal combination of water quantity and quality for each initial state; but do not take into account the effects of accumulation of salt over time.

Bresler and Yaron (1972) develop a short-run model to obtain the optimal quantity-quality combination of irrigation water in a single irrigation season via linear programming. Yaron et al. (1980) present a dynamic programming model for irrigation scheduling with explicit consideration of soil salinity parameters. They use two discrete state variables, soil moisture and soil salinity, to characterize the modeling system. Gini (1984) develops a short-run model that simulates the dynamics of water allocation and salt movement in a two-layered soil column. He includes nonlinear differential equations describing the water and salt balance in the unsaturated and saturated zones in the model. Mass and Hoffman (1977) apply the critical salinity approach to estimate yield reduction from excessive salinity in the root zone. This model uses contours of equal crop yield reduction as a function of the initial salt concentration in the unsaturated zone and the salt concentration of the irrigation water.

Long-term models. A long-run model accounts for the effects of salt accumulation in the soil profile over time. This type of model comprises a succession of short-run processes and the initial conditions, which are affected by salt accumulation in the previous periods. Irrigation decisions over a single season take into account the resulting conditions and their effects on succeeding periods.

Yaron and Olian (1973) present a long-run model for the analysis of a winter leaching policy on a perennial crop in a Mediterranean climate. In their model, a stage is defined as a year consisting of a rainy season (winter) and a dry season (summer). The state variable is the mean chloride concentration in the soil profile at the end of a rainy season, and the decision variable is the quantity of water used to leach the soil profile at the end of the rainy season. Matanga and Marino (1979) modify this model to take into account seasonal irrigation depth as another decision variable. The authors also extend this model to multiple crops and then investigate optimal area-allocation among crops.

Bras and Seo (1987) develop a conceptual model to describe the dynamics of water allocation and salt movement in the root zone of a crop. They combine moisture stress and osmotic stress to obtain the integrated inhibitory effect of salinity on transpiration. The long-term prevention of salt accumulation is handled via probabilistic state constraints with imposed salinity and moisture levels with desired confidence levels.

Bresler, Yaron, and Segev (1983) consider soil variability and uncertainty via stochastic modeling in a long-run mixed integer linear program. In their study, soil properties are regarded as random variables, characterized by their probability density function. The authors include the average and variance of log transforms of some random parameters such as the saturated hydraulic conductivity and the recharge rate into the model, and use the prescribed probabilities of root zone salinity exceeding a given critical concentration as constraints. This approach, incorporating soil science and economic analysis, is considered to be realistic for the irrigation management of natural heterogeneous fields.

Extended long-term models. An extended long-run model takes into account both the salt accumulation in the soil profile and its accumulation in groundwater. In this case, flow and contaminant transport in both soil and aquifers is considered (see, for example, Hanks and Andersen 1979; Lefkoff and Gorelick 1990a; Musharrafieh et al. 1995; Peralta, Kowalski, and Cantiller 1988; and Peralta et al. 1990). Another group of models deals with irrigation scheduling problems, which can be viewed as a finite horizon stochastic multistage decision process (Bras and Seo 1987). At each stage– after the state of the system has been determined– a decision is made, which affects the dynamics and the performance measure of the system. Stochastic dynamic programming is an ideal solution scheme for this feedback control problem. However, it is often computationally impractical or infeasible to implement due to dimensionality problems. Dynamic programming has been used to solve many short- and long-term models, while interactive simulation and optimization techniques have been used to solve extended long-run models. Linear programming and the linear-quadratic approach have also been applied for quantity-quality management in irrigated agriculture (Bras and Seo 1987).

Runoff irrigation modeling. All models discussed above consider conventional irrigation, generally starting from rivers, lakes, and aquifers for irrigation water supply. Runoff irrigation, originating in rainfall descending from higher to lower elevations, can be used to supplement or replace conventional irrigation in arid areas. Generation of runoff can be simulated by mechanistic models that study and model the microscopic level of runoff formation, progressively increasing the modeled scale, and by empirical models that infer the runoff-producing patterns of catchments with different sizes from the input/output relations of the watershed properties. There is a broad literature on precipitation-runoff models for agricultural purposes and the interested reader is referred to Ben-Asher and Berliner 1994, from which a brief summary of models is presented below.

Agricultural watersheds can be divided into micro-catchment water harvesting (MCWH) and small catchment watershed harvesting (SCWH). In MCWH, surface runoff is collected from a small runoff-contributing area and stored in the root zone of an adjacent infiltration basin to meet crop water requirements (Prinz 1990). MCWH is especially useful in arid and semiarid regions, where irrigation water is either costly or unavailable. Examples of models developed for the quantitative evaluation of MCWH include the kinematic wave model by Zarmi, Ben-Asher, and Greengard (1982), which offers an analytical prediction of MCWH hydrographs on a short-term basis; the numerical model by Bores et al. (1986), which provides a linkage between the hydrologic processes in the contributing area and the water uptake by a tree in the collecting area, and thus describes the complete MCWH process; and the stochastic model by Ben-Asher and Warrick (1987), which takes into account spatial and temporal variability of soil properties and precipitation.

From a hydrologic point of view, SCWH differs from MCWH by the number of channels through which runoff can flow before reaching the cultivated area. SCWH can be described as a runoff water harvesting system subject to large variability in soil and hydraulic properties of the contributing area. The runoff efficiency of SCWH is affected by the Partial Area Contribution (PAC) phenomenon. There are three major approaches for modeling the rainfall-runoff relationship for SCWH: (1) the deterministic one-dimensional model (Klemm 1990); (2) the parametric modeling of the entire watershed (Dodi, Ben-Asher, and Adar 1987); and (3) the modeling of the watershed on the basis of the PAC concept (Karnieli et al. 1988; Ben-Asher and Humborg 1992).

From the point of view of water management, the combination of runoff and conventional irrigation in arid and semiarid areas in a systematic framework is of particular importance. Whereas conventional irrigation can be controlled (and thus studied) more easily, runoff irrigation depends heavily on the stochastics of precipitation, and structural measures, like reservoirs, are less effective. Environmental sustainability in arid areas will likely benefit from a joint application of conventional and runoff irrigation, facilitated through a combination of infrastructure and other hardware and policies and other software measures.

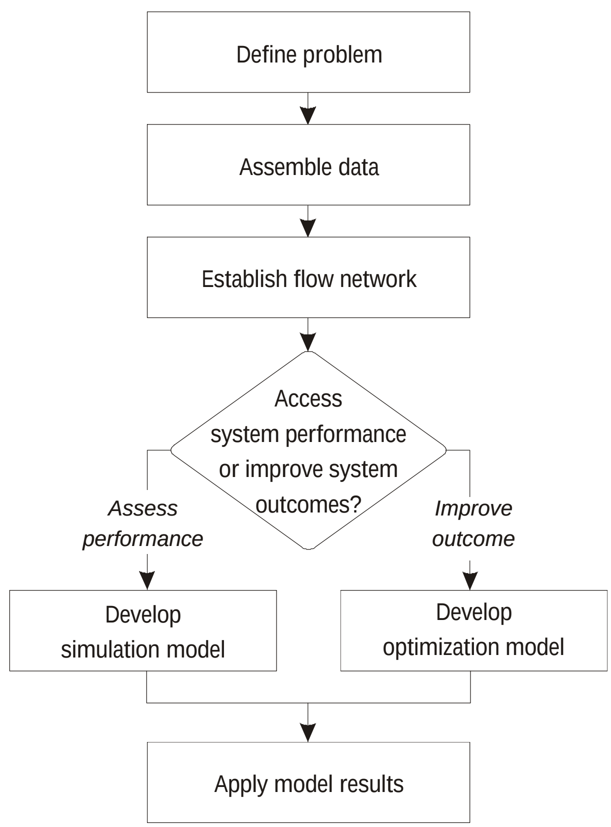
Water Resources Management Modeling at the River Basin Scale

Introduction

After a short overview of the evolution of basin-scale water models, this section presents a review of mathematical models for the optimal management of water resources at the river basin scale.

Of particular importance to basin-scale analyses are models of two fundamental types: models that *simulate* water resources behavior in accordance with a predefined set of rules (actual or hypothetical) governing water allocations and infrastructure operations, and models that *optimize* and select allocations and infrastructure based on an objective function (economic or

FIGURE 3.
Schematic view of the complementary application of basin-scale models.



other) and accompanying constraints. Figure 3 presents a schematic view of the complementary application of these types of basin-scale models. Whereas the assessment of system performance can best be addressed with simulation models, optimization models are more useful if improvement of the system performance is the main goal. Models can also simultaneously include simulation and optimization capabilities.

In optimization models, especially at the basin scale, hydrologic interactions among principal water sources and their uses might be described in less detail than they might be in order to capture the broader resources dynamics. Given the considerable volume and complexity of data and analyses required to support policy decisions at the basin scale, models of the type reviewed here clearly represent the best scientific approach to identifying, testing, and successfully implementing rational and efficient water resources allocation strategies.

Evolution of basin-scale models

The design and application of mathematical models to predict hydro-meteorological processes can be traced to Richardson 1922. The potential of computers to solve numerical models representing complex hydrologic processes was harnessed during the rapid expansion of the water resources infrastructure in the 1950s and 1960s. Given the computational limitations imposed by nascent computer hardware and software, the focus of early water resources models was primarily restricted to planning and design. However, the need to combine economic and hydrologic considerations in water resources systems was recognized. Significant early advances in the development of combined models are presented by Maass (1962).

Following earlier basin models, particularly the 1956 SSARR Streamflow Synthesis and Reservoir Regulation (USACE 1972) and the 1960s National Weather Service's Sacramento model (Burnash, Ferral, and McGuire 1973), the SIMYLD-II model (Texas Water Development Board 1972) systematically applied network flow programming techniques to the simulation of reservoir-river systems. As both numerical representations and computers became more sophisticated, model emphasis shifted from engineered systems with clearly defined decision and control variables to natural systems in which human interventions were analyzed in a broader environmental systems context. As a result, operations and resources management became the focus of model development. Expensive computer access and run-time coupled with cumbersome input of often scarce data ensured that models remained the exclusive domain of specialized users located in government and academic research institutions.

However, with the advent of personal computers, user-friendly model interfaces, and public-domain information access during the 1980s, water resources models were rapidly acquired and widely applied by private and public organizations. Today, there is a plethora of models designed to address a wide range of water resources problems. The reader is referred to Wurbs 1995 for an in-depth review of models developed in the United States. Additional models are covered by UN (1994). Models have also been developed and successfully applied by a range of organizations around the world, including the International Institute for Applied Systems Analysis (IIASA), the Institute of Hydrology in Great Britain, the World Meteorological Organization (WMO), and the International Ground Water Modeling Center in Colorado, USA. In the following, selected models are reviewed, which are important from the perspective of making optimal use of water resources in a river basin context.

Simulation models

Basin-scale models that use hydrologic input data (historical, stochastic, or hypothetical) and simulate the behavior of various hydrologic, water quality, economic, or other variables under a fixed set of water allocation and infrastructure management policies have been widely used to assess the performance of water resources systems. A distinguishing feature of these simulation models, as opposed to optimization models, is their ability to assess performance over the long term (typically, over the period of reliable forecasts for flows and demands). Consequently, simulation is the preferable technique to assess water resources system responses to extreme, nonequilibrium conditions, and thereby to identify the system components most prone to failure, or to evaluate system performance relative to a set of sustainability criteria that may span decades. In particular, hydrologic simulation models play a critical role in assessing the performance of water resources systems under scenarios of global climate change (Loaiciga et al. 1996), drought (Young 1995), and rapidly changing priority demands, such as those driven by accelerated municipal growth.

River basin flow simulation models. Among the wide range of simulation modeling efforts the models that simulate river basins are of particular interest. In the United States, simulation models have been applied successfully to manage water resources systems. The application of the Long Range Study (LRS) model for the Missouri River, the Potomac River Interactive Simulation Model (PRISM), and the Colorado River Simulation System (CRSS) and its offshoots are reviewed by Wurbs (1995). Loaiza García and Jiménez Ramón (1987) apply a network flow programming simulation model to assess the potential of constructing several reservoirs to augment the municipal water supply for Monterrey, Mexico. These models, while providing robust simulation tools for the particular basin in question, were not designed to be generalizable to other river systems.

A related class of models allows for user-defined nodes, links, operating rules, and targets, among others. The AQUATOOL model has been applied to the Segura and Tagus river basins in Spain and continues to be used by the River Basin Agency of the Tagus river. AQUATOOL integrates simulation, risk, optimization (of the type described in the next section as hydrologic optimization), and groundwater analyses; however, the model is limited by its lack of water quality analyses, a feature to be incorporated in future versions (Andreu, Capilla, and Sanchis 1996). Dunn et al. (1996) report on the application to the Cam basin in the United Kingdom of the NERC-ESRC Land-Use Programme (NELUP) model with associated economics, ecology, and hydrology sub-models.

River basin quality simulation models. Increasingly, water quality simulation capability is a standard feature of river basin models. Early models were dimensionless, with assumptions of complete mixing and only time-dependent variation of relatively straightforward water quality variables including temperature, dissolved oxygen (DO), and biochemical oxygen demand (BOD). Subsequent models that introduced spatial variability, were one-dimensional in the direction of flow, and allowed for the simulation of more complex variables subject to adsorption or decay processes, such as nutrients and coliforms. More recently, fully three-dimensional, time-dependent models incorporating many realistic processes affecting water quality have appeared.

In the United States, the most widely accepted water quality model is the Enhanced Stream Water Quality Model (QUAL2E), distributed by the United States Environmental Protection Agency (EPA 1998). QUAL2E simulates temperature, DO, BOD, chlorophyll A, nitrogen (organic N, ammonia NH_3, and nitrate NO_3^-), phosphorus (P, organic and inorganic), and coliforms in addition to constituents with user-defined decay properties. QUAL2E is a standard tool in the formulation of environmental impact statements. The Water Quality for River-

Reservoir Systems (WQRRS) developed by the United States Army Corps of Engineers, Hydrologic Engineering Center, simulates DO, total dissolved solids, P, NH_3, NO_2^-, NO_3^-, alkalinity, total carbon, organic constituents, and a range of aquatic biota including plankton, algae, coliforms, and several fish species (as described in Wurbs 1995; USACE 1998). WQRRS is hydrodynamic, that is, it models the hydraulics of flow, predicting depth and velocity. The latter variable is particularly important for the simulation of sediment and water quality constituents bound to sediment, such as metals. While there has been considerable interest in the transport and fate of heavy metals in river basins, the weak link from a modeling perspective has been the simulation of the transport of metals bound to sediments– these processes are based on variable hydrodynamics and nonstationary boundary conditions.

River basin water rights simulation models. To realistically simulate water allocations to different uses, the prevailing system of water rights in a basin must often be explicitly accounted for. Models have been formulated specifically to handle priority allocations based on water rights. The Texas A&M University Water Rights Analysis Package (TAMUWRAP) handles the prior appropriation ('first in time, first in right') system of legal water rights in the western United States (Wurbs, Dunn, and Walls 1993). The model simulates hydrologic flows, multiple-reservoir operations, and salinity under diversions to multiple uses with a set of priority allocations, each defined by annual volume, priority number, type of use, and optional water rights group. TAMUWRAP has been applied to the Brazos river in the state of Texas, where over 1,300 permit (rights) holders are legally allowed to use water from a system of 12 reservoirs.

In an extensive study of the impact of a severe, sustained drought on water resources in the Colorado river basin in the United States, several models were applied and adapted to account for interstate water rights in accordance with the 1922 Colorado River Compact and related legislation. The complementary use of simulation, optimization, and gaming models to assess the drought impacts for the Colorado river is outlined in figure 4. The Colorado River Network Model (CRM) is capable of simulation and optimization; however, for this study, it was adapted to simulate priority-based allocations (Harding, Sangoyomi, and Payton 1995). As part of the same study, the Colorado River Institutional Model (CRIM) was developed and applied to simulate and optimize water allocations under a variety of market and nonmarket arrangements (Booker 1995). CRIM accounts for basin-wide priorities, including USA treaty obligations with Mexico. It is coded in the General Algebraic Modeling System (GAMS) and is solved by its nonlinear solver, MINOS (Brooke, Kendrick, and Meeraus 1988). The results indicate that nonconsumptive uses of water (particularly hydropower and recreation) are consistently undervalued by the current set of rights based on consumptive uses (agriculture and municipal water supplies).

Part of the Colorado river drought study includes an interactive, gaming simulation of the drought, where riparian states and the federal government are represented by players with information on the status of water resources resulting from their own real-time decisions regarding intrastate water allocation (Henderson and Lord 1995). Using the AZCOL river model, which is based on the CRM simulation model described above and assembled in the STELLA II modeling environment, three games were played with rules based on existing compact agreements, a hypothetical interstate basin commission, and water markets. Based on water market rules, a win-win situation was identified where lower basin states could buy long-term rights from the upper basin with the legally enforceable provision that upper basin short-term deficits would be covered with water purchased back from the lower basin.

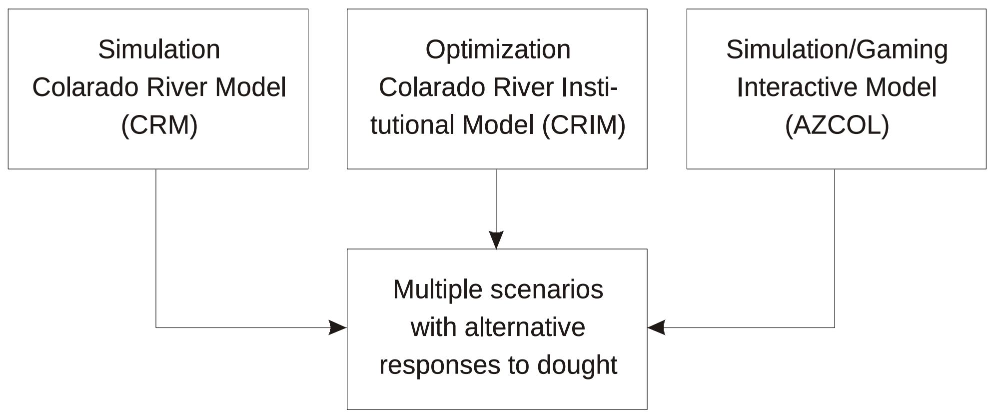
FIGURE 4.
The application of multiple, complementary models to assess the drought response for the Colorado river.

Problem Definition: Assess the infrastructural, economic, and instituional responses to a severe sustained drought on the Colorado river.

Data Assembled: Historical flows and drought conditions reconstructed from tree-ring records.

Modeling Tools:

Model Outputs:



Study Outcomes: Recommendations to riparian states and federal government on policy options with institutional, economic, and technical measures aimed at improving drought response.

Comprehensive river basin simulation systems. Interactive models of the type just described, accompanied by graphical user interfaces for the on-screen configuration of the simulated system and display of results, have become increasingly available and often are the models of choice for river basin simulation. The Interactive River-Aquifer Simulation (IRAS) model in its earlier versions introduced advanced graphics capabilities to facilitate user interaction in all stages of system simulation. The current IRAS version simulates flows, storage, water quality, hydropower, and energy for pumping in an interdependent surface water-groundwater system. The water quality component allows up to 10 independent or interdependent constituents with first-order kinetics and one-dimensional advection and dispersion. The new IRAS version is operated under Windows 95/NT, uses a relational database, includes sediment transport, and allows for modular interfacing with a watershed runoff component, or other user-defined modules. IRAS has been applied in India, Canada, the United States, Russia, and Portugal where it has been selected as the model for water resources negotiations with Spain (Loucks, French, and Taylor 1995).

The Tennessee Valley Authority's (TVA) Environment and River Resource Aid (TERRA) model is a reservoir and power generation operations management tool linked to a local area network for the real-time functioning of the complex TVA system (Reitsma, Ostrowski, and Wehrend 1994). Auxiliary hydrologic and hydraulic simulation models are used to determine operational schedules; however, TERRA is unique in that it manages hydrometeorological input and processed output data for a range of users with different levels of security access. TERRA was designed specifically for the TVA system and is not intended to be a generalizable model for other river basins.

The WaterWare model was developed by a consortium of European Union-sponsored research institutes from the United Kingdom, Spain, Ireland, Italy, and IIASA (Jamieson and Fedra 1996a). WaterWare runs on a UNIX platform and contains analytical components for demand forecasting, water resources planning, and groundwater and surface water pollution. It has a GIS display with special filters to import GIS maps in several commercial formats and incorporates embedded expert systems. Modular architecture allows WaterWare to draw on a number of sub-models, for example, a two-dimensional, finite-difference groundwater model (Jamieson and Fedra 1996b). WaterWare has been applied to the Thames river basin in Great Britain, the Lerma-Chapala basin in Mexico, and the West Bank and Gaza in Palestine.

The European Hdyrological System (SHE) has been developed as a joint effort by the Institute of Hydrology in Great Britain, SOGREAH (France), and the Danish Hydraulic Institute (DHI) (Abbott et al. 1986). SHE is a distributed and physically based modeling system for describing the major flow processes of the entire land phase of the hydrologic cycle. One version, the MIKE SHE (DHI 1995) has a number of add-on modules applied according to some specific problems in the river basin, such as water quality, soil erosion, or irrigation. MIKE SHE is being used operationally by several universities, research organizations, and consulting engineering companies. The MIKE BASIN is another water resources management tool developed by DHI. It is structured as a network model in which the rivers and their main tributaries are represented by a network consisting of branches and nodes. MIKE BASIN uses a graphical user interface with a linkage to ArcView GIS. The model output includes information on the performance of each individual reservoir and irrigation scheme within the simulation period, illustrating the frequency and magnitude of water shortages. The combined effect of selected schemes on river flows can also be handled through simulating the time series of the river flow at all nodes (DHI 1997; 1998).

Optimization models

Models that optimize water resources based on an objective function and constraints must have a simulation component, however rudimentary, with which to calculate hydrologic flows and constituent mass balances. A distinct advantage of optimization models over simulation models is their ability to incorporate social value systems in the allocation of water resources. In this section, two basic types of optimization approaches are reviewed. The first type could be described as hydrology-inferred optimization in that the model's objective functions for intra-sectoral allocation are derived from hydrologic specifications. The second type refers to economic optimization models that optimize allocations inter-sectorally based on optimal water allocation. Other criteria, such as equity or environmental quality can also be used.

Related to the reservoir operation models described above, but with an expanded set of state variables, are several hydrologic optimization models developed for intra-sectoral water allocation. Vedula and Mujumdar (1992) and Vedula and Kumar (1996) describe a stochastic dynamic programming model with numerous simplifications that solves for minimum crop yield reductions caused by water stress. In dynamic programming, transformation functions are determined, which link the values of the state variables in each time period to those in subsequent periods, to allow for the calculation of the objective function value. This disaggregation of the objective function into a series of recursively solved equations for multiple state variables introduces significant computational complexity, also referred to as the "curse of dimensionality."

Ponnambalam and Adams (1996) report on the application of the Multilevel Approximate Dynamic Programming (MAM-DP) model for the operation of multiple reservoirs. MAM-DP minimizes the difference between water supply and demand, while explicitly attempting to reduce the number of state variables, thus easing the computational load resulting from the problem's dimensionality. The model was applied to the Parambikulam-Aliyar Project in India with two interconnected basins, and is operated in the context of treaty provisions for the multi-annual rights of two riparian states.

The mathematical formulation of a strict economic optimization approach (*sans* flow simulation) is presented by Babu, Nivas, and Traxler (1996). The state variables are water table depth, salinity, water availability, and cropping intensity; the control variables are investments in unlined and lined canals, public and private drainage, and private tube wells. Functions, presumably empirical in practice, relate control and state variables. From the (nominal) basin-level approach adopted for this model, salinity and waterlogging impacts are internalized.

McKinney and Cai (1996) and McKinney, Karimov, and Cai (1997) develop hydrology-inferred policy analysis tools to be used for water allocation decision making at the river basin scale. This work involves the development of optimization models for the Amu Darya and Syr Darya basins in the Aral Sea basin of Central Asia using GAMS and ArcView GIS software. This hydrology-inferred approach has been extended recently to an economic optimization approach that considers cropping decisions and irrigation and drainage system improvements.

Integrated simulation and optimization

As has been mentioned, basin-scale optimization models must be able to characterize the hydrologic regime to calculate the objective function. Optimal water allocation must also be feasible, at a minimum from an infrastructure operation's perspective, for policy makers and system managers to consider their adoption. In the following, several models that integrate simulation and economic optimization capabilities with the goal of policy analysis are reviewed.

Labadie, Fontane, and Dai (1994) extend MODSIM, a widely used simulation package for river basin network flow modeling to directly include water quality regulations as constraints. The new model, MODQSIM, handles water quality predictions and projections through a linkage with QUAL2E. QUAL2E is used to update water quality coefficients in MODSIMQ, and MODSIMQ calculates both network flows and concentrations, which are then fed back into QUAL2E for further simulation. This approach is similar to that of Dandy and Crawley (1992) but improves on some of the limitations in that study.

The CRIM model described above also includes combined simulation/optimization components in its application to drought conditions (Booker 1995). The effects of the following policy responses to drought are examined under the objective of minimizing economic damages resulting from drought (excluding salinity): (1) store water as high in the basin as possible to reduce evaporative losses; (2) maintain hydropower capability; (3) shift to proportional sharing of shortfalls; (4) shift shortfalls to agriculture, the largest consumptive water user; (5) adopt intrastate market allocation mechanisms; and (6) adopt interstate markets. CRIM identified both intrastate and interstate markets as representing optimal allocation strategies.

EUREKA-ENVINET INFOSYST constitutes a sophisticated decision-support system for integrated river basin management that was initiated in Europe in 1992. This system is expected to provide the water industry with a methodology for planning and managing water resources, including rivers, aquifers, lakes, reservoirs, estuaries, and coastal waters in a sustainable manner (Fedra, Weigkricht, and

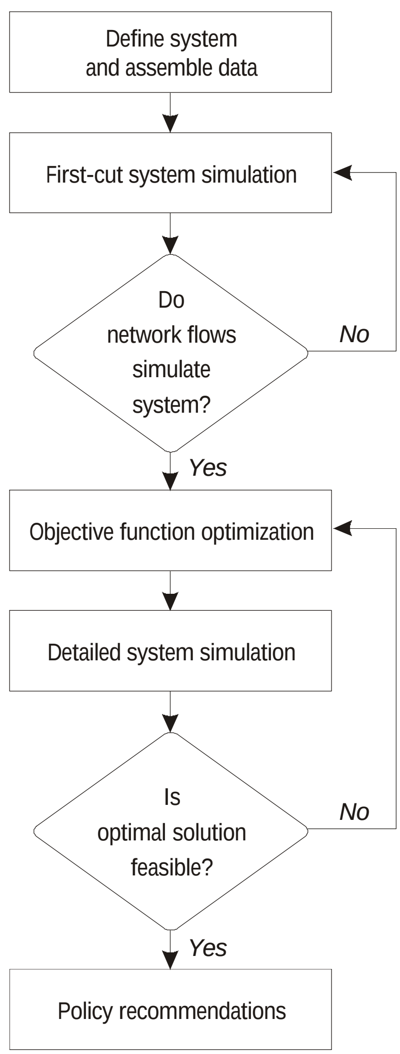
Winkelbauer 1993). It is designed to integrate GIS, database management systems, modeling capability, optimization techniques, and expert systems.

Lee and Howitt (1996) model water and salt balances in the Colorado river basin to determine salinity levels that maximize net returns to agriculture and municipal-industrial (MI) users at select locations in the basin. Nonlinear crop production functions and MI costs per unit of salinity are derived for inclusion in the objective function, which was solved using the GAMS/ MINOS software. Three scenarios are considered: (1) economic optimality; (2) no change in cropping patterns with subsidies for salinity control measures; and (3) cropping changes with subsidies to maintain agricultural profits. The first-best, economically optimal scenario indicates major declines in cropped area with significant returns to MI uses. Of the two scenarios with subsidies, the cropping changes subsidized to maintain profits indicate marginally lower total subsidies with a minor, but significant reduction in salinity. The authors note that optimal solutions were modeled without consideration of transaction costs or equity criteria.

Tejada-Guibert, Johnson, and Stedinger (1995) develop an optimization approach emphasizing hydropower generation in the face of uncertain inflows and demands and apply it to the Shasta-Trinity system in California, USA. The model uses stochastic dynamic programming (SDP) to account for inflow series based on four predictive schemes: (1) simple yearly and monthly averages; (2) probability distribution; (3) Markov chain; and (4) sophisticated streamflow and snowmelt hydrology. The model is run with variable demand and shortfall penalties and system performance was evaluated.

Faisal, Young, and Warner (1994) apply integrated simulation-optimization modeling of water resources systems to groundwater basins. The hydrologic flow regime is characterized by a linear response matrix, which allows the superposition of the effects of pumping at different aquifer locations on the particular location where drawdown is to be simulated. The location-to-location drawdown functions, however, are derived using the MODFLOW three-dimensional finite-difference groundwater model. The conjugate gradient method was applied to solve the optimization of the nonlinear objective function. The authors model two scenarios: (1) the social optimal for the basin, and (2) the

FIGURE 5.
Sequential optimization and simulation model application to derive feasible and optimal policy alternatives.



common pool optimum consisting of self-interested farmers. While discounted net benefits for the two scenarios are not markedly different, the common pool results in significantly reduced aquifer levels.

Simulation and optimization models of basin-scale water resources systems are complementary research tools to address problems related to the competition over scarce water resources and the design and assessment of alternative systems of water allocation. The basic data requirements and understanding of system operations are generic to both types of models. The sequential application of both types of models represents perhaps the best approach, as indicated in figure 5.

A first-cut simulation of the system ensures that flows, storage volumes, releases, and diversions in the model reflect reality (actually a model calibration step). The subsequent formulation and application of the optimization model determine the values of a set of policy variables that optimize the system operation. A more detailed simulation model based on the optimization model-determined policy then serves to assess their feasibility with regard to infrastructure operations as well as to identify system components with the potential for failure under extreme conditions. Policy interventions regarding allocation mechanisms, which stem from this process, are likely to result in outcomes that are both efficient and feasible.

Economics in Water Allocation

Introduction

It is only by considering all interactive components that benefit from or damage the resource that optimal use from a social standpoint can be established. Thus, with the growing scarcity of water and increasing competition for water across sectors, economic issues in water allocation are increasing in importance in river basin management. Rosegrant and Meinzen-Dick (1996) identify the following economic concepts and issues that need to be examined through integrated economic-hydrologic river basin modeling:

Transaction costs

What investment and transaction costs (information, metering, conveyance, contracting, adjudication, and enforcement) are associated with different allocation mechanisms? What institutions (public and private) are necessary to establish and maintain these services? What institutional mechanisms are most effective in minimizing the associated costs?

Agricultural productivity effects

What are the impacts of alternative water allocation mechanisms on farmer water use, choice of inputs, investments, productivity of water, agricultural production, and income in different agroeconomic and scarcity environments? How do institutional forms and institutional effectiveness mediate these impacts?

Inter-sectoral water allocation

How do allocative mechanisms divide water between agriculture and nonagriculture? Is the inter-sectoral allocation of water economically efficient under alternative water allocation mechanisms? Do different mechanisms favor particular sectors? What are the implications of the growing competition between agriculture and nonagriculture for the availability and productivity of water in agriculture? How have allocative mechanisms responded to this pressure?

Environmental impacts

What is the relationship between alternative allocation mechanisms and environmental externalities caused by irrigation, such as waterlogging, salinization, groundwater mining, and groundwater recharge? Does the assignment of tradable property rights lead to internalization of externalities and reductions in externality costs? What is the effect of upper watershed degradation on productivity and resources degradation in downstream agriculture? Of the two choices of dealing with the economic impact of this type of degradation at the source or within the downstream areas which is more effective? How can costs of remediation be equitably allocated and payments effectively transferred?

Property rights in water

What are the *de jure* and *de facto* property rights in water for different categories of users under alternative allocation mechanisms? How are water rights obtained: prior use, administrative allocation, purchase, or investment in infrastructure? What are the characteristics of rights in terms of seniority, consumptive use versus diversion rights, and proportional rights versus fixed quantity rights? How are water rights linked (or delinked) with land rights under alternative allocation mechanisms? Are water rights transferable within and among water-using sectors? What are the equity and efficiency implications of alternative types of property rights in water in conjunction with different allocation mechanisms?

Integration of economics into river basin models requires the incorporation of production functions for agriculture that include water as an input, and demand functions for water for domestic and industrial use, to estimate the use and value of water by sector. It is also highly desirable to estimate the value of other types of demand for water within the river basin, including environmental demands, water quality, recreational demand, and hydropower. This section reviews alternative methods for measuring the value of water in agricultural and nonagricultural uses.

Valuation of Water for Agricultural Uses

Crop production functions with water

The fundamental building block for the estimation of the demand for and value of water in the agriculture sector is a production function that relates crop production to the use of water and other inputs. An ideal crop-water production model should be flexible enough to address issues at the crop, farm, or basin levels. The production function should allow the assessment of policy-related problems, and results should be transferable between locations. In addition, the model should be simple to operate, requiring a small data set; easily adjustable to various farming conditions; and sufficiently comprehensive to allow the estimation of externality effects. In addition, the interaction between water quantity and quality and the water input/production output should be clearly defined (Dinar and Letey 1996).

Existing modeling approaches to crop-water relationships (for example, surveys by Hanks 1983; and Vaux and Pruitt 1983) address economic, engineering, and biological aspects of the production process. These surveys conclude that crop-water relationships are very complicated and that not all management issues have been fully addressed in one comprehensive model. In the following, the advantages and disadvantages of alternative production functions are summarized.

Types of production functions. Four broad approaches to production functions can be identified: evapotranspiration and transpiration models, simulation models, estimated models, and hybrid models that combine aspects of the first three types. The following overview on production functions related to water use draws heavily on Dinar and Letey 1996, chapters 2 and 3, for the first three types of models.

Evapotranspiration and transpiration models. Evapotranspiration models are physical models that predict crop yield under varying conditions of salinity levels, soil moisture conditions, and irrigation strategies. They assume a linear yield-evapotranspiration relationship and are usually site-specific and very data-intensive (see also Hanks and Hill 1980).

A basic yield-seasonal evapotranspiration relationship is represented by:

$$Y/Y_{max} = 1 - kc^*(1 - E/E_{max})$$

where,

Y = actual yield (tons/ha),
Y_{max} = maximum dry matter yield (tons/ha),
kc = crop coefficient,
E = actual evapotranspiration (mm), and
E_{max} = maximum evapotranspiration (mm).

The parameter E can be estimated by

$$E_{max} = w + r + \Delta q - o - d$$

where,

w = applied water (mm),
r = rainfall (mm),
Δq = change in soil water storage (mm),
o = runoff, and
d = drainage.

Transpiration models use a similar approach but measurement of transpiration is more difficult because it is difficult to separate it from evaporation. Although evapotranspiration and transpiration models capture important aspects of crop-water relationships, they have limited ability to capture the impacts of non-water inputs, and are of limited use for policy analysis.

Simulation models. Within the category of simulation models, Dinar and Letey (1996) distinguish between *holistic* simulation models that simulate in detail the production process of one crop and *specific* models that focus on one production input or the subsystems associated with a particular production input.

Detailed, data-intensive holistic models have been developed for most of the basic crops and a series of other agricultural production features: PNUTGRO for peanut (Boote et al. 1989); SIMPOTATO for potato, CERES for maize (Jones and Kiniry 1986), SOYCROS for soybean (Penning de Vries et al. 1992); spring wheat (van Keulen and Seligman 1987). See also the CAMASE register, which currently includes more than 200 agro-ecosystem models or similar registers (CAMASE 1997). COTMOD, a model for cotton, for example, can be used to simulate the effects of various irrigation schedules, fertilizer application rates, and other management practices on cotton yield (Marani 1988). The relatively complicated data-generation through field experiments and calibration procedures prevents the easy transferability of this model.

Stockle, Martin, and Campbell (1994) present a robust model, CropSyst, which enables the simulation of various crops with regard to nitrogen and water decisions. The model was calibrated for corn at Davis, California, USA, and was successfully transferred to other locations. EPIC (Erosion Productivity Impact Calculator) was developed to assess the relationship between soil erosion by wind or water and soil productivity in terms of crop yield in the United States. The model has also been used in other countries (Williams et al. 1989).

Specific models are less comprehensive, but still need a complex set of site-specific field experiments for data generation and a lengthy process of model calibration. Cardon and Letey

(1992) formulate a soil-based model for irrigation and soil salinity management in semiarid areas. This model allows, among others, the treatment of growth-stage-specific crop tolerance to salinity or water stress; temporal variation in potential transpiration and rooting depth-distribution; and multiseasonal simulation capability through allowance of non-cropped periods.

Dinar and Letey (1996) specify a model, in which annual applied water, irrigation water salinity, published coefficients relating crop sensitivity to salinity, the relationship between yield and evapotranspiration, and the maximum evapotranspiration for the area are the input parameters. Outputs include crop yield, amount of drainage water, and salinity of the drainage water. It is assumed that all non-water-related inputs are applied at the optimum level. Water is the only limiting factor in the production process.

Estimated production functions. Estimated production functions are more flexible than other model types. However, specification and estimation procedures must comply with plant-water relationships: (1) plant yield increases as water quantity increases beyond some minimum value; (2) yield possibly decreases in a zone of excessive water applications; (3) yield decreases as the initial level of soil salinity in the root zone or the salt concentration in the applied irrigation water increases beyond some minimum value; and (4) the final level of root zone soil salinity decreases with increasing irrigation quantities–except for possible increases, where relatively insufficient water quantities have been applied (Dinar and Letey 1996).

To meet these requirements, polynomial functions have been applied in many production functions. Dinar and Letey (1996) present the following quadratic polynomial form in the case of three production inputs:

$$Y/Y_{max} = a_0+a_1\, w+a_2\, s+a_3 u+a_4\, w.s+a_5\, w.u+a_6\, s.u+a_7\, w^2+a_8 s^2+a_9 s^2+a_9 u^2$$

where,

- Y = yield,
- Y_{max} = maximum potential yield,
- w = water application to potential evapotranspiration,
- s = salinity of the irrigation water,
- u = irrigation uniformity, and
- a_i = estimated coefficients (i=1,..9).

The quadratic form implies that an increase in the level of one of the decision variables results in a constant change in the level of the dependent variable up to a point. Any further increase results in an opposite response (positive-diminishing marginal-productivity zone on the production surface), followed by a zone of negative marginal productivity. Moore, Gollehon, and Negri (1993) use farm-level census data from the western United States to estimate crop water production functions for 13 crops in Cobb-Douglas and quadratic forms. Van Liebig response functions for nutrients and water have been estimated using experimental data. They appear to outperform polynomial functional forms (Paris and Knapp 1989). However, they are rarely applied as they require detailed field-level data. Berck and Helfand (1990) find that crop yields are better approximated by a smooth concave function.

Hybrid production functions. Hybrid models, which draw on the strengths of each production function approach, may offer considerable advantages to the three types of approaches taken individually. As noted above, each of the three basic methodologies for production functions has some weaknesses. Particularly limiting may be the data requirements for any given approach. It is likely that, for some relationships embodied in the model, available experimental and nonexperimental data, especially on the interrelationships of water use, resource degradation, and production, may be inadequate. Several reasons can account for this. Nonexperimental data (cross-section and time series data) collected by government agencies or targeted surveys can rarely adequately measure or control water and important environmental variables (like water table depth and soil and water quality). Generation of this type of data can also be difficult, expensive, and often impractical, if not impossible, to achieve.

In many instances, however, data are not entirely absent. If data are relatively sparse, the available observations may not be adequate for statistical analyses but they can be useful in calibrating generalized versions of simulation models. When important biophysical and environmental variables in the study are inadequate or unavailable, simulation models can be used to generate pseudo-data. Pseudo-data are not true historical data, but are derived from process models replicating the real-world processes in computer experiments. Observations are generated by repeatedly solving the model for different initial values, and by parametrically varying input or output quantities and values. Simulation models are practical substitutes for complex biophysical experiments (or even for nonexperimental data), where it is often difficult to isolate the impacts of important policy, management, or environmental variables on output variables. In simulation models, the analyst can control institutional, technological, and environmental factors, which is not possible with real-world experiments. Application of pseudo-data to irrigation and engineering problems includes Dinar and Letey 1996 and Rosegrant and Shetty 1994.

A variation of this approach is the calibrated production function approach developed by Howitt (1995). The production technology in all linear programming models is locally linear in all inputs, including land. Quadratic specifications that include endogenous prices and risk terms add some nonlinearities but do not change the linear stepwise specification of regional production. Howitt (1995) suggests calibrated production equilibrium (CPE) models as a compromise between the data-intensive econometric models and inflexible linear programming models. The empirical calibration procedure uses a three-stage approach. First, a constrained linear program is specified, and then, the regional production and cost parameters that calibrate the nonlinear CES model to a base-year date are derived from numerical results of the linear program. Finally, a third-stage model is specified with a nonlinear objective function that incorporates the nonlinear production functions and land costs. The calibration process can also incorporate detailed information on physical crop-water relationships.

Optimization of water use— mathematical programming models

Production functions describe the relationship between the utilization of water and crop output. But estimation of the demand for water and the resultant value of that water in production require also a decision rule to determine the farmer's joint choice of a cropping pattern, water application levels, and irrigation technologies, conditioned on input costs and output prices. Therefore, to be used within a river basin model to assess farmer water allocation decisions, production functions for crops grown within the basin are generally embedded within an optimization framework. Optimization in the context of river basin modeling was discussed in some detail above; here we discuss the use of optimization for farmer decision making. Optimization of farm-level returns to irrigation is usually undertaken by applying mathematical programming techniques. A mathematical programming framework involves the optimization of an objective function subject to the underlying production technology and constraints on water and other resources. The objective function, for example, could be to maximize net returns with respect to choice of crop, inputs, use of irrigation water, investment in irrigation technology and management, and transfer of irrigation water to the nonagriculture sector.

The underlying production technology for such an optimization framework can be specified by the production function approaches described above, with production functions specified for each crop within the feasible set of crops, by location in the river basin. More commonly in the literature, technology has been represented by Leontief-style fixed proportion input-output coefficients combined with linear constraints. The linear programming approach has the advantage that it can be implemented with a minimum of data for those problems in which the fixed proportion input assumption and linear constraints are reasonable approximations of reality. Bowen and Young (1985) provide a good example of a linear programming model, deriving estimates of financial and economic net benefits to irrigation water supply for a case study area in the northern Nile delta region of Egypt. The authors formulate linear programming models of representative farms in the study area and report total, average, and marginal net benefit functions. Nonlinear programming models extend the linear programming approach to permit nonlinear production technology and constraints. Other examples of linear programming models include that of Buller et al. (1991) who use a linear programming model to estimate the most profitable combination of irrigated crops; and Balasubramamiam, Somasundarum, and Pundarikanthan (1996) who analyze a tank irrigation system in India. Lee and Howitt (1996) develop a nonlinear mathematical programming model that optimizes river water quality, resources allocation, production levels, and total expenditures for water control, and apply it to the Colorado river basin. As Young (1996) notes, most applications of mathematical programming for the analysis of water use in agricultural production have been partial equilibrium, deterministic, and static.

However, extensions of the partial equilibrium, deterministic, and static approaches are now being increasingly used. Bryant, Mjelde, and Lacewell (1993) develop a dynamic programming model to optimally allocate a predetermined number of irrigations between two competing crops. The model also allows for stochastic weather patterns and temporary or permanent abandonment of crops. The assumed objective is maximization of expected net returns from both crops for the given number of irrigations over a single year. Dudley (1988) uses dynamic programming to examine optimal land and water use in irrigated agriculture. Knapp and Wichelns (1990) review the use of dynamic programming models for salinity and drainage management. Srivavasta and Patel (1992) use both linear and dynamic programming for the Karjan Irrigation Reservoir Project in India. The authors find that linear programming is best suited for determining reservoir capacity, whereas dynamic programming could be used to further refine the output target and to determine the possible reservoir carryover storages. Finally, Wu, Mapp, and Bernardo (1994) develop a dynamic model to analyze farmers' irrigation investment and crop choice decisions under alternative water quality protection policies and apply it to the Oklahoma High Plains in the United States.

Berck, Robinson, and Goldman (1991) present a computable general equilibrium (CGE) model of agricultural water use in the San Joaquin Valley of California. Other CGE models include that of Robinson and Gehlhar (1995) who model arable land and water scarcity in Egypt to analyze the consequences of instituting a market for water and charges for water used in agriculture. In the same context, Löfgren (1995) studies the economy-wide consequences of various mechanisms to increase water prices for agricultural uses, and of a water supply rationing scheme, and Mukherjee (1996) builds a watershed CGE for the Olifants river in South Africa, to study inter-sectoral water allocation.

Dudley and Burt (1973) apply stochastic dynamic programming to determine the optimal combination of reservoir size and irrigated acreage. Their early analyses are limited to a single crop. Dudley, Reklis, and Burt (1976) apply a hierarchy of models to extend the analysis to multiple crops: they develop a linear programming model to allocate water among the crops, a simulation model to estimate water supply, and a stochastic dynamic programming model to optimize water delivery over time. Paudyal and Manguerra (1990) use a two-step (deterministic and stochastic) dynamic programming approach to solve the problem of optimal water allocation in a run-of-river-type irrigation project. Ziari, McCarl, and Stockle (1995) develop a two-stage model, in which they simultaneously consider multiple crops, stochastic water supply and demand, water application, and risk attitude. The first-stage ('here and now') decisions involve investment choices such as the type of irrigation system and the size of the runoff impoundment structure. In the second stage, the crop mix is specified depending on the first stage. The objective function includes both expectation and variance terms for risk aversion. The authors find that supplemental irrigation could provide not only an increase in expected benefits but also a substantial reduction in risk. Finally, Taylor and Young (1997) use discrete stochastic sequential programming to examine multi-crop production processes in irrigated agriculture.

Valuation of Nonagricultural Demand for Water

Nonagricultural uses of water include domestic demand for household activities; demand for commercial, industrial, and mining uses, including hydropower, cooling, condensation, and factory and mining production; recreational demand; and demand for environmental purposes such as maintenance of in-stream river flows and flushing of pollutants. Important complications in the valuation of nonagricultural water in many instances include (1) the absence of well-delineated water markets where water may be valued; (2) non-rivalry and non-excludability in water consumption; and (3) the physical mobility of water that makes the accurate approximation of a water price difficult. There are two general approaches that have been used in inferring the value of nonagricultural water uses: market-based valuation techniques, and nonmarket-based valuation techniques.

The market-based techniques include the direct estimation of water demand functions (when observable prices are available), the sales comparison method, the land-value differential approach, and the least-cost alternative approach. Nonmarket approaches include inferential valuation or revealed preference, which involves the imputation of implicit prices, in terms of expenditures incurred by individuals in using the resource; and stated preference or contingent valuation, which elicits direct responses of potential users to structured survey questions regarding the amount they are willing to pay for water services.

Market-based valuation techniques

The benefits from household or industrial water consumption can be estimated as the consumer surplus derived from a demand function from water. The consumer surplus measures the excess in monetary value that an individual or firm would be willing to pay for a good above the total expenditures that would be made at a fixed price. Estimates of consumer surplus are generally derived from a demand function, which is a schedule of the different quantities of goods purchased at various levels of prices, with quantity purchased inversely related to changes in prices. The market demand for water is linear and downward sloping. A typical household or industrial water demand function is represented by a range of natural and socioeconomic factors (Young 1996):

$$Q_w = Q_w(P_w, P_a, P; Y; Z)$$

where,

Q_w = level of consumption,
P_w = price of water,
P_a = price of alternative water source,
P = average price index representing all other goods and services,
Y = consumer's income, and
Z = other factors (climate and consumer preferences, for example).

The substantial literature on estimation of household demand functions for water has been summarized by Gibbons (1986) and Schneider and Whitlach (1991). More recent studies estimating demand functions for water include those by Lyman (1992); Hewitt and Hanemann (1995); and Dandy, Nguyen, and Davies (1997). The vast majority of household or municipal water demand estimates are from developed countries, but some analyses have also been done for developing countries. Abu Rizaiza (1991) estimates residential water usage in the major cities of the western region of Saudi Arabia, based on a cross-sectional analysis of 400 households. Residential water uses among the cities differ according to differneces in income, temperature, and price of water. The estimated price elasticity for houses supplied by the public network is –0.48, very similar to the values found in industrialized countries. Woo (1992) uses time series data for Hong Kong to estimate a model of urban water consumption under service interruption. He finds that an interruption policy of 8 non-served hours per day may lead to a small reduction in per capita water use of about 6 percent, and estimates that the same level of demand reduction can be achieved by an increase in prevailing prices of 16 percent that, in turn, reduces the burden caused by interruptions of the service on households and small industrial firms. Cestti (1993) estimates household water demand functions for piped water, groundwater, and for vendor water in the Jabotabek region, Indonesia. The equation of best fit for the piped water demand function is explained by average water price, income level, alternative source, and problem areas. In a literature review of 27 studies on residential water demand Cestti, Yepes, and Dianderas (1997) find that water demand tends to increase with family income and that the water price is negatively related to water use. Other explanatory variables (*Z,* in the above formula) include the residency's characteristics and climate conditions. The price elasticities rank from –0.10 to –0.36, with an average value of –0.21, and the effect of water use due to a price increase is gretaer in the long run than in the short run.

For industrial demand functions, other explanatory factors (Z variables above) tend to include the prices of other factor inputs, the type of technology or production process, the product mix, and output levels. Although relatively few studies have examined the structure of the industrial demand for water, demand elasticity estimates obtained were highly variable depending on the industry being studied, the functional forms used, and the specification of the demand function. Cestti (1993), for example, finds that the location of the industry and the type of investment are highly relevant for the industrial water demand in the Jabotabek region, Indonesia. Using single equation models, demand for industrial water has been explained by variations in price, commonly calculated as total expenditures on the reuse of water (Rees 1969; Turnovsky 1969; and DeRooy 1974); as cited in Renzetti 1992. Using cross-sectional data on state level, Grebenstein and Field (1979) and Babin, Willis, and Allen (1982), (also mentioned in Renzetti, 1992), estimate a translog cost function using water, labor, capital, and the price of water, measured as average cost.

Estimation of the value of water from household and industrial demand functions is well-grounded in theory, and methodological approaches for estimation are well-specified. However, the availability of data can be a significant problem, explaining, for example, the relative paucity of studies in developing countries. Time series data on water demand are often inaccessible, and cross-sectional data often do not exhibit adequate variation in prices to generate robust estimates.

In addition to direct estimation of demand functions, the value of household water uses has also been estimated by real estate appraisal techniques that link water rates or fees exacted for water diverted for residential purposes to the market value of purchasing or selling water rights. These methods include the sales comparison technique, the income capitalization technique, and the land-value differential technique (Saliba and Bush 1987, p. 205). The sales comparison method compares the price of a particular water right to the prices of similar rights that had been recently sold in the market. This method of calculating water values results in a band or range of prices within which the value of the water right could possibly fall. In the land-value approach, the value of the water right is calculated as the difference in land values between land with and without access to water or water rights. This approach is often used in the valuation of water in irrigated agriculture, through comparison of the value of irrigated and nonirrigated land (Young 1996). It is also directly applicable to pricing municipal water. The information on the differences in market sales of residential lots with and without water rights (or with different quantities and qualities of water) allows the estimation of the value of the water rights and the price that urban consumers are willing to pay for water use.

Other market valuation techniques estimate the value of existing water supplies as the cost of obtaining new water supplies. The least-cost alternative method estimates the equivalent costs of an alternative or alternatives to acquiring the rights to already developed water. These costs could be derived from the costs of recycling of water or constructing a new water supply, which may include the costs of pumps and well drilling, the construction of a pipe system to bring water from the source to the destination, and other related costs. This approach is commonly used in pricing water for industrial purposes and in hydropower production, but can be extended to municipal uses if it can be established that consumers would be willing to buy water at prices equivalent to the development cost of the water source (Saliba and Bush 1987). The extraction cost method incorporates into the analysis the investment costs required to generate new sources of water supply in water pricing. If investment costs are not included, the price of water based only on the average costs incurred in the development of the water supply, treatment cost, and distribution cost tend to underestimate the true value of water (Moncur and Pollock 1988).

The sales comparison, the differential land values of dry properties and properties with access to water, the least-cost alternative methods, and the extraction cost method are straightforward and simple procedures to empirically assess water prices. Because only secondary data are required, calculating water prices based on these techniques may be less costly to undertake in comparison to methods that require survey or field data. Although these methods economize on research costs, the use of secondary data raises other issues that should also be considered in selecting the appropriate method to use. Generally, information systems in developing countries remain poorly developed, raising serious concerns among researchers and policy makers on the correctness of estimates of water prices derived from each of the aforementioned market-based procedures.

Economic value of hydropower generation

The pure economic value of the in-stream water use of hydropower generation can be measured as the amount of power generated times the difference of price minus cost per unit of power generated. The amount of potential power generation per unit of water depends on both natural conditions at the location and on the investment in water storage and generating facilities at the site and the efficiency of the generating facilities. To calculate power generation for a hydropower station with a reservoir, for example, the following general equation applies:

$$POWER = C * \eta * h * Q * \Delta t$$

where,

- C = a constant for unit transformation (reflecting the theoretical kilowatt hours generated per unit volume per unit head),
- η = production efficiency, depending on turbine and generator conditions,
- h = average water head during a time period, calculated as the difference between reservoir elevation and tail water elevation [L],
- Q = average release rate through the turbine [L3/T], and
- Δt = change in time t.

Thus, the production of electricity is a function of the water head and the release rate during a specific time period. The long-term hydropower generation is subject to the uncertainty of reservoir inflow.

Once the amount of electricity generated is estimated, a number of issues arise in the economic valuation of this electricity. The value of hydropower generated can be measured based on the avoided cost of a second-best alternative, or on the cost of producing a marginal unit of electricity from alternative methods of power generation. To undertake this assessment, the analyst must distinguish what type of alternative power source the hydropower generation is replacing and if hydropower generation displaces base load or peak load facilities. Maximum allowable daily flows and other constraints also must be taken into account. Finally, valuation of hydropower can be done on either a short-run or long-run basis. Short-run valuation of hydropower, which takes account of the value of operations and maintenance costs, is appropriate in the context of short-run water reallocation issues. Long-run valuation, which must also account for annualized investment costs for hydropower development, is appropriate for longer-term investment and allocation decisions. More details on assessment of the overall economic feasibility or the long-term economic value of hydropower generation are given by Young (1996).

Nonmarket techniques

Nonmarket approaches to valuation of water include inferential valuation or revealed preference methods and contingent valuation methods. Revealed preference methods involve imputing implicit prices for (1) access to a resource, in terms of expenditures incurred by individuals in utilizing the resource or for (2) characteristics of a resource, such as water quality. The contingent valuation method elicits direct responses of potential users to structured survey questions regarding the amount they are willing to pay for water services or for specified hypothetical changes in the quantity or quality of goods or services. A large body of literature has developed in the past 20 years on valuing public goods with nonmarket techniques. Carson et al. (1997) cite that almost 2,000 studies dealing with contingent valuation of natural resources alone have been carried out. In this section, applications are described for the valuation of water by each of the main types of nonmarket valuation techniques.

Among the revealed preference techniques the most widely used is the travel cost method (TCM). It is typically applied to assess the value of water quality and recreation-based benefits but it can also be used to estimate the value of residential water to consumers. The value is usually estimated by regressing the intensity of use of a specific source or sources, as measured by the number of trips made to recreation sites, water wells, pumps, kiosks, or other outside sources, against the transportation costs required to use the source or sources. The TCM can be extended by inputing additional costs that may be incurred, such as the opportunity costs of wages foregone and costs of time spent fetching water. For a critique of the TCM see Randall 1994.

The hedonic pricing method also derives benefit estimates based on revealed choices about related goods (Cropper and Oates 1992). The hedonic method relies on the notion that the price of marketed goods can be decomposed into its attributes, and that an implicit price exists for each of these attributes. From a sample of closely similar marketed goods, implicit prices can be estimated with econometric techniques that reflect the value of the different characteristics of that good. The partial derivative of the hedonic price function with respect to the attribute of interest (like water quality) yields a measure of the marginal value of that attribute. This approach is often used for the aesthetic or quality valuation of water resources. Irrigation water supply has also been valued using this approach, through estimation of the effect of availability of water on the value of farmland (Young 1996).

Another alternative method used to value water or environmental quality more generally is variously called averting behavior, averting costs, avoidance costs, and defensive expenditures or technology. This method relies on the fact that, in some cases, purchased inputs can be used to mitigate negative environmental effects. For example, farmers can increase the irrigated area and other inputs used to compensate for yield decreases due to salinization and consumers can take actions to avoid drinking polluted groundwater or mitigate the health effects of poor quality water. Given that purchased inputs can be used to compensate for the effects of pollution or changes in water quality, the value of a change in pollution can be measured by the value of the inputs used to compensate for these quality changes (Cropper and Oates 1992; Lee and Moffit 1993).

In the stated preference approach or contingent valuation technique method (CVM), survey respondents are offered conditions simulating a hypothetical market in which they are asked to express how much they are willing to pay for an existing or potential environmental condition of water quantity or quality not registered on any market. The technique is termed 'contingent' because the provision of the good or service is hypothetical. Although contingent valuation is widely employed, responses to contingent valuation questions may be biased. For example, if future charges for water are perceived to be directly correlated with possible gains that could be obtained from use of a particular water source over an alternative source, an individual may underestimate the amount of water fee he or she is willing to pay. However, such biased responses may disappear if payments are perceived to be dispersed among or shared by a wider number of users. Thus, unless the questionnaires are well-administered and questions clearly laid out, personal valuations revealed by potential users may be seriously biased. Most importantly, perhaps, the cost of conducting the field survey in developing-countries may be prohibitively high to warrant the use of contingent valuation over market-based valuation techniques that rely on less-costly secondary data. To assure an accurate result, extreme care must go into the design and conduct of the survey, particularly the definition of the good or service being valued. Despite these concerns, recent evidence indicates that results from CVM are quite consistent with those from revealed preference approaches. Carson et al. (1996) compare 83 studies containing 616 estimates using both CVM and revealed preference. The mean ratio of CVM to revealed preference estimates for the full sample is 0.89, and the Pearson correlation coefficient between the two types of estimates is 0.83.

In developing countries, application of the contingent valuation technique evolved from water supply and sanitation to recreation, tourism, and national parks, to surface water quality, health, and biodiversity conservation (Whittington 1998). A pioneering application of CVM for developing-country household water demand evolved from the effort of the World Bank Water Demand Research Team (see reference section in World Bank Water Demand Research Team 1993). In selected regions of Latin America, Africa, and South Asia, CVM was applied by asking households in a series of hypothetical questions whether they would choose improved water services at a specified price or connection fee. This study found that a number of factors significantly affected household decisions to obtain better-quality water, including education, occupation, size and composition of household, income, expenditures, wealth, the cost of fetching water, water quality, reliability of supply source, and attitudes towards the government.

Choe, Whittington, and Lauria (1996) apply CVM and TCM to estimate the economic value that people in Davao, the Philippines place on improving the water quality of the rivers and the seas near their community. The authors find that the estimates from the analyses of the responses to the contingent valuation questions and the recreation patterns and travel costs of residents of Davao are very similar and are quite low, both in absolute terms (about US$1–2 per month per household) and as a percentage of household income (< 1%).

Shabman and Stephenson (1996) contrast the results of the use of contingent valuation, hedonic price, and property damages avoided techniques in estimating the value of flood risk reduction from the construction of a flood control project in Roanoke, Virginia (USA). The hedonic price technique generated the largest benefit estimates for reduced flood risk along the Roanoke river, with a mean estimate of US$1,333, followed by the property damages avoided technique, at $597, and the CVM, at $314. The authors conclude that there may be no single 'true' behavior if preferences vary across time and between choice-making circumstances, but that the choices observed are more likely constructed than retrieved from previously formed preferences.

Benefit Functions for Water in a River Basin Context

Benefit functions for water are closely related to the demand function concept introduced above. A benefit function for water is a form of inverse demand function, which expresses the value as a function of quantity. It permits direct measurements of the change in benefits associated with increments or decrements in water supply. The use of relatively aggregated benefit functions may be particularly useful in river basin modeling when data and resources do not permit estimation of disaggregated production functions and household and industrial demand functions.

Booker and Colby (1995) provide a comprehensive set of economic demand functions for competing uses for the Colorado river basin. Marginal benefit functions, which measure economic value as a function of water supply, were developed for in-stream and off-stream uses. Irrigation benefit functions are derived from linear programming models of water allocation options under site-specific soil, climatic, and market conditions. The linear programming models are formulated to yield a net benefit for each point on a hypothesized range of water availabilities.

For the agricultural demand function, a single marginal benefit or (inverse demand) function is estimated by least squares regression (Cobb-Douglas form):

$p(x) = p_0\ (x/x_0)\alpha$

where,

$0 < x_0 < x$

x_0 = maximum water delivery,

p_0 = willingness to pay for additional water at full delivery, and

α = inverse of the price elasticity of demand.

The underlying demand schedules include meaningful marginal benefit values for use reductions to approximately $0.5x_0$.

The total benefit, *V(x)*, of water use *x* is specified as

$V(x) = x_0\ v_0\ (x/x_0)\beta$

where,

x = actual water use,

v_0 = $p_0/(1 +$ “), and

β = (1 + “).

Here, it is assumed that alternative water sources are used in a fixed amount.

The total benefit from municipal use of water is

$$V_c\ (x^1) = (x_n + x_0)v_0\ \{[(x_n + x^1)/(x_n + x_0)]\ [x_n/(x_n + x_0)]\}$$

where,

x^1 = actual use of river basin water, and

x_n = actual use of non-river-basin water.

As this equation shows, the aggregate benefit function approach can be implemented with relatively few parameters, and thus can be an effective approach under conditions of sparse data.

Integrated Economic-Hydrologic Models

Introduction

Despite the critical importance of economic variables in water resources allocation and management, water resources studies have generally been dominated by hydrologic studies for flood control management and water resources planning from an engineering point of view. At the same time, economic or policy analysis studies have usually focused solely on profit maximization of water uses for irrigation, industrial, and domestic purposes, conditioned on the amount of water supplied at the offtake or delivery point. However, management of water resources requires an interdisciplinary approach, integrating natural and social sciences. Combined economic and hydrologic studies at the river basin level are best equipped to assess water management and policy issues (Young 1995). Recent modeling studies more readily recognize the necessity of integrated approaches, but usually either the economic or the hydrologic component dominates, depending on the researchers and on the set of issues examined. Whereas hydrologic-based studies account for hydrologic and system-control components in a comprehensive and detailed way, the economic component is represented by cost-benefit analyses or aggregate water delivery objectives. On the other hand, the emphasis in economic studies has been mainly on input/output analyses and on the optimization of net benefits without comprehensive hydrologic modeling.

The aspects discussed by Braat and Lierop (1987) for economic-ecological modeling also apply to economic-hydrologic modeling: the modeled relationships should allow for the effective transfer of information from one component to the other. A number of barriers must be overcome to achieve the goal of integration. Hydrologic models often use simulation techniques whereas, frequently, economic models use optimization, often causing difficulties in information exchanges between the two components. The boundaries considered in the economic system– political and administrative– might not be the same as those of the hydrologic system. The two components also may have different spatial development horizons, which refer to the area over which impacts and developments extend, as well as the area (or volume) over which the model can be validated. In addition, the economic and hydrologic components often use different time intervals and time horizons. Economic models use generally larger time intervals (seasonal or annual) and longer time horizons (for example long-term forecasts), whereas in hydrologic models, the time interval has to be small enough to reflect the real-world processes, and the horizon is generally restricted by computation capacity and data availability. However, hydrologic simulation models can have a far larger time horizon. Data requirements and availability might further constrain the integrative aspects of this approach. The task of future modeling of water allocation at the river basin level is to overcome these obstacles through integration of rigorous economic relationships into comprehensive hydrologic river basin models, in order to simultaneously determine supply and demand for water and economic benefits to water within the basin. In this way, the operation of the hydrologic system (for example, reservoir system, stream-aquifer system, or river basin system) is driven by a socioeconomic objective (or multiple objectives including socioeconomic and environmental objectives); the water right covering both water quantity and quality is directly simulated or constrained by hydrologic modeling; and the water market is built on the physical system. More importantly, water will be traded at the optimal state of the physical system, which results from the hydrologic technical operation induced by economic incentives.

There are two approaches to develop integrated economic-hydrologic models: the *compartment* modeling approach and the *holistic* approach. Under the compartment approach there is a loose connection between the different economic and hydrologic components, that is, only output data are usually transferred between the components. The various (sub-)models can therefore be very complex, but the analysis is often more difficult due to the loose connection between the components. The main research question is: which mathematical formats are available to transform information between the economic and hydrologic models? Under the holistic approach, there is one single unit with both components tightly connected to a consistent model, and an integrated analytical framework is provided. However, the hydrologic component is often considerably simplified due to model-solving complexities. This approach requires the use of one single technique (simulation, dynamic programming, etc.) and one single denominator for the variable quantities. The information transfer between economic and hydrologic components remains a technical obstacle in the compartment modeling approach, while in the holistic modeling approach, information transfer is conducted endogenously. The compartment modeling approach is likely more realistic for application, but further research is needed into the development of more appropriate dynamic connections, through which the economic and hydrologic components can be solved in an interactive way. For the holistic modeling approach, the key issue will be to define the essential relations between the economic and hydrologic components so that the economic analysis can be realized based on a meaningful physical system.

The Compartment Modeling Approach

Several researchers have examined the effectiveness of economic incentives, water conservation, and quality control for managing water. Howe and Orr (1974) extend earlier works (for example, Hartman and Seastone 1970; Gardner and Fullerton 1968) concerning the use of marketable water rights to include considerations of saline pollution. Moreover, Cummings and McFarland (1974) derive an analytical framework through which they analyze decision rules for groundwater conservation and salinity control via taxes and bribes. All derivations and analyses are based on simple groundwater flow and salt balance equations (but both are transient equations); the potential impact of irrigation on the quality of groundwater and possible externalities is ignored. Involving such complexities should provide more implications, but this kind of extension has not been explored in the literature. The reason might be that including these complex issues would make such in-depth economic analyses much more difficult.

A notable research effort in integrating economic modeling and complex hydrologic modeling is reported by Noel and Howitt (1982) who incorporate a quadratic economic welfare function (Takayama and Judge 1964) into a multi-basin conjunctive use model. Several economic (derived demand, opportunity cost, and urban demand) and hydrologic (groundwater, and surface water potential) auxiliary models are applied to derive linear sets of first-order difference equations which formed a so-called linear quadratic control model (LQCM). This model is then used to determine the optimal spatial and temporal allocation of a complex water resources system and to examine the relative performances of social optimal policy, pumping tax policy, and laissez-faire policy.

More recently, Lefkoff and Gorelick (1990a) used a mathematical format to transform information between the economic model and the hydrologic model different from that of Noel and Howitt (1982). They combine distributed parameter simulation of stream-aquifer interactions, water salinity changes, and empirical agronomic functions into a long-term optimization model to determine annual groundwater pumping, surface water applications, and planting acreage. The authors apply the microeconomic theory of the firm, associated with agronomic functions related to water quantity and quality for each farm during each season for farmers to choose a level of production where marginal revenue equals marginal cost. The salinity changes are expressed by regression functions, which were derived from Monte Carlo simulation solutions of the salt transport equation that uses random values for climatic and water use variables. Lefkoff and Gorelick (1990b) further extend the model to incorporate a rental market mechanism, considering annual water trading among farmers. Results from the extended model show that the market increases long-term profits for all participants, reduces the risk of loss due to drought, and decreases average short-term groundwater salinity.

Lee and Howitt (1996) use nonlinear regional production models and a hydrology model to analyze the economics of externalities in irrigated agriculture in the Colorado river basin. They apply a Cobb-Douglas production function including land, capital, water, and water quality for the regional production models. The hydrology model provides the physical linkage between upper-basin water use and salt loading and lower-basin water salinity and allows a simultaneous solution of the basin-wide model equations.

A critical concept for integrated economic-hydrologic modeling is to combine short-run and long-run effects in an appropriate manner so that short-run effects can be adequately reflected in the long run. Feinerman and Yaron (1983) present a linear programming model, deterministic in the short run and stochastic (random rainfall) in the long run. The short-run model, limited to a single year, incorporates the physical, biological, and economic relationships involved in one endogenous system. This model is used to analyze the economic significance of various parameters, optimal solution values, shadow prices, and rates of substitution between the limited resources. The long-run model considers the effects of the short-run decisions on the stream of future profits and rainfall uncertainty, but several relationships are incorporated exogenously. These relationships, including irrigation water mixing, soil salinity ranges, crop yields, and net profits, are predetermined based on the results of the short-run model. The hydrologic aspects are highly simplified in this study, and several interesting extensions are suggested by the authors, including a hydrologic restriction on irrigation water mixing and taking seasonal irrigation depth as an additional decision variable and soil moisture content as an additional state variable. This study is limited to a single farm, and neither marketing nor externalities are considered.

The Holistic Modeling Approach

Harding, Sangoyomi, and Payton (1995) use the Colorado River Network Model (CRM) to study the hydrologic impacts of a severe drought in the Colorado river. This network flow model uses an algorithm to perform a static optimization representing the water allocation for a given set of priorities in a river basin network at each time-step. Booker and Young (1994) present a nonlinear optimization model for investigating the performance of alternative market institutions for water resources allocation at the river basin scale. This model is built on the optimization model of market transfer exemplified by Vaux and Howitt (1984), and extensions are made on both the supply and the demand side. On the supply side, the flow balance and transfer, and the salt balance are adapted to the Colorado river basin network including river nodes, reservoir nodes, hydropower station nodes, and demand site nodes; on the demand side, both off-stream (irrigation, municipal, and thermal energy) and in-stream (hydropower and water quality) are represented by empirical marginal benefit functions. This model is used to estimate impacts of alternative institutional scenarios, river flows, and demand levels. Based on the model results, the authors argue that interstate consumptive use markets alone would not efficiently allocate Colorado river basin water resources, and inclusion of nonconsumptive use values would be necessary for regional equity.

Booker (1995) extends the basin model reported in Booker and Young (1994) to an integrated hydrologic-economic-institutional optimization model, CRIM– the Colorado River Institutional Model. The extension includes more realistic (yet still relatively aggregate and crude) hydrology, more disaggregated economic data, and the modeling of more institutional choices. The model is used to estimate the economic and hydrologic impacts of drought in the Colorado river basin, and to model alternative policy responses to drought. Formulated as an optimization problem, nonlinear in the objective function and constraints, the model simultaneously solves the economic impact and water allocation problems, subject to assumed policy scenarios. Economic and hydrologic factors are included as constraints, while institutional factors are primarily simulated in the objective function. For estimating economic losses due to drought, CRIM uses the benefit functions reported by Booker and Colby (1995). The model is solved on an annual basis. CRIM is written in GAMS and solved with the MINOS nonlinear solver. The estimates of water use and benefits, flows, storage, and evaporation closely match the CRM (Harding, Sangoyomi, and Payton 1995).

Henderson and Lord (1995) integrate the studies by Booker (1995), Booker and Colby (1995), Harding, Sangoyomi, and Payton (1995), and Hardy (1995) into a gaming-type model, to simulate potential collective action processes.

Their AZCOL model is used to identify improved operating rules for the Colorado river basin. The players are represented by the states in the basin and the United States Secretary of the Interior. The gaming is conducted under collective choice rules that approximate the existing rules, as well as under two modified sets of rules considered to be attainable without specific additional legislation. The principal findings are that the operating rules selected by the players were similar in the different games; the operating rules favor consumptive water use over nonconsumptive uses, like hydroelectric power generation, environmental protection, salinity control, and recreation. (This conclusion was even stronger when reasonable weights were given to nonmarket factors.); the existing decision-making institutions do not allow for identification of collective interests and actions; and the existing rules needlessly constrain flexibility in allocation between upstream and downstream uses and users. Faisal, Young, and Warner (1997) study a problem of groundwater basin management in which economic objectives were combined with realistic aquifer responses through the use of discrete kernels. The integrated model is formulated as a consistent inter-temporal resources allocation problem. This model includes nonlinear quadratic crop production equations, and is solved via a conjugate gradient based on a nonlinear programming algorithm.

The integrated economic-hydrologic water allocation models described above have been synthesized in table 1.

GIS-Based Decision Support Systems

Introduction

Decision support systems (DSS) based on geographic information system (GIS), often known as spatial decision support systems (SDSS), are a class of computer systems in which the technologies of both GIS and DSS are applied to aid decision makers with problems that have a spatial dimension (Walsh 1992). GIS is a general-purpose technology for handling geographic data in digital form, with the ability to preprocess data into a form suitable for analysis, to support analysis and modeling directly, and to post-process results (Goodchild 1993). GIS offers a spatial representation of water resources systems, but currently few predictive and related analytical capacities are available for solving complex water resources planning and management problems (Walsh 1992; Parks 1993). DSS are interactive programs, often with a graphical user interface (GUI), which embed traditional water resources simulation and optimization models, with adaptation of new approaches, to support users in semi-structural or ill-structural problem solving (Loucks and da Costa 1991). An extension of the DSS concept, spatial decision support systems (SDSS), which are the integration of DSS and GIS, was initiated by Densham and Goodchild (1988). The research potential for SDSS in water resources was addressed by Walsh (1992). SDSS integrate spatial dimension and modeling capacity into an operational framework, so that DSS and GIS technology can be more robust by both their linkage and coevolution.

Both GIS and DSS have been widely used in water resources. Watkins and McKinney (1995) present a recent review on DSS in water resources; and Goodchild et al. (1996) describe a comprehensive study of GIS in water resources and environmental engineering. Singh and Fiorentino (1996) give a recent, comprehensive

TABLE 1.
Classification of integrated economic-hydrologic water allocation models.

Model	Modeling approach[a]					Model features[a]				Add comp[b]	Issues[c]	Policies	Source
	Com	Hol	Sim	Opt	GIS	SW	GW	ST	LT				
AZCOL		X	X			X	X	X		IN	A,D,I,E	Water market	Henderson and Lord, 1995
Unnamed								X			A		Howe and Orr, 1974
WRAP		X	X			X	X	X	X	IN	A,D,I,E	Water right	
Unnamed	X							X			A	Taxes	Cummings and McFarland, 1974
Unnamed	X						X	X			A, D		Noel and Howitt, 1982
Unnamed	X							X			A		Lefkoff and Gorelick, 1990a
Unnamed	X							X		IN	A	Water trading	Lefkoff and Gorelick, 1990b
Unnamed	X							X			E		Lee and Howitt, 1996
Unnamed	X		X	X		X	X	X	X				Feinerman and Yaron, 1983
CRM		X		X		X		X					Harding, Sangoyoui, and Payton, 1995
CRIM		X		X		X		X		IN	A,D,I,E	Water market	Booker, 1995
Unnamed	X		X	X		X	X	X			E		Louie, Yeh, and Hsu, 1984
Unnamed		X		X		X		X		AR	A,D,I,E	Market institutions	Booker and Young, 1994
Unnamed		X		X		X						Water market	Vaux and Howitt, 1984
Unnamed		X		X		X					A,D,E	Policy response to drought	Booker, 1995
Unnamed		X		X		X					A,D,E		Henderson and Lord, 1995
Unnamed		X		X			X				A		Faisal, Young, and Warner, 1997

[a]Modeling approach: Com = Compartment; Hol = Holistic; Sim = Simulation; Opt = Optimization; SW = Surface water; GW = Groundwater; ST = Short-term; LT = Long-term.
[b]Add. components: Economic and hydrologic components are assumed; AR = Agronomic; IN = Institutional.
[c]Issues addressed: A = Agriculture; D = Domestic; I = Industry; and E = Environment.

review of GIS in hydrology. Compared to traditional DSS, SDSS have been improved through the incorporation of GIS. Three aspects, database, interface, and model connection illustrate the major advantages of using a SDSS for river basin management. Some of the studies taking advantage of these characteristics to solve complex problems in water resources planning and management are reviewed in the following.

Features of GIS-Based Decision Support Systems

Comprehensive database

A database is the basis for any DSS. A GIS not only brings spatial dimensions into the traditional water resources database, but also, more significantly, has the ability to better integrate the various social, economic, and environmental factors related to water resources planning and management for use in a decision-making process. Therefore, such a system helps attain an integrated view of the world. New concepts, such as hierarchical spatial data structure and object orientation, make the databases more robust and comprehensive.

Lam and Swayne (1991) develop an environmental information system, RAISON, which combines database, map, spreadsheet, and statistical analysis components from environmental, social, economic, agricultural, and other sources. Lam and Pupp (1996) report on the application of using the neural network method for estimation of the missing data, and on the use of expert system technology for treatment of spatial and temporal scales, degrees of accuracy and uncertainties. Cowan et al. (1996) describe an ongoing large-scale project to develop integrated information systems to manage human use of the environment. Those systems are expected to deal with the 'information gridlock' problem because current information, while often expensive, is fragmented, inconsistent, underutilized, and often inaccessible. The authors also discuss organizational issues in the implementation of integrated information systems.

Csillag (1996) suggests the use of hierarchy in spatial data structures to manage the enormous amounts of data required by environmental modeling. Hierarchical data structures, like quadtrees, were shown to transparently link the data and the model, and to statistically integrate uncertainty in space, time, attributes, and representation. Goodchild and Yang (1992) address the concept of hierarchy for global geographic information systems. Goodchild (1993) proposes a conceptual framework of fields and objects. Fields represent the spatial variation of a single variable using a collection of discrete objects, and objects are modeled as points, lines, or areas. A spatial database contains many such fields and objects. The most relevant concept involved in object-oriented databases is 'inheritance,' which means that an object can inherit properties of its parents, or its component parts. Crosbie (1996) argues that object-oriented databases have many advantages compared to conventional, relational, or hybrid databases.

Interactive interface

The visual display capacity of GIS and the graphical user interface of DSS enhance the user interface of a SDSS, which allows the user to take more complete control of data input and manipulation. Sophisticated user interfaces can provide user-defined triggers, which allow the user to dictate how features will respond to environmental changes, and to construct rules to control the modeling process (Crosbie 1996). The ease and flexibility in which any water resources system can be defined, modified, and visualized through the designed interface should bring ease and flexibility to modeling and result-analysis (Loucks, French, and Taylor 1996).

Fedra and Jamieson (1996) describe an object-oriented information and DSS for river basin management, called WaterWare. Three kinds of objects are defined in WaterWare: River Basin Objects, representing real world entities; Network Objects, representing abstraction of the real world entities; and Scenario Objects, representing model-oriented scenarios of Network Objects that are partially derived from, and linked to, the River Basin Objects. These objects and various analysis functions can be manipulated within a common interface designed in a multimedia framework, and information for decision support is therefore translated through the interface. Reitsma (1996) introduces a similar interface designed in the River Simulation System (RSS) (CADSWES 1993). Through the interface of RSS, the user can build a modeling network by querying a georelational database for the river elements, or graphically draw the network.

Djokic and Maidment (1993) propose a toolbox approach or SDSS shell through which all the capacities of respective technologies and commercially available software, including GIS, expert systems, and numerical models become available in a unified computer environment. A case study was demonstrated for a SDSS shell integrating ARC/INFO, Nexpert System and HEC-1.

Pundt et al. (1996) propose an interface for transferring data. They store data collected through field work in different formats (including raster, vector, and textual), and transfer these data to a spatial DSS via several import-export interfaces. This is expected to promote a greater compatibility and flexibility with commercial general purpose GIS.

GIS in modeling

For solving water resources problems, both a spatial representation of the water resources system and an insight into water resources problems are necessary (Walsh 1992). GIS has been applied to provide the former and water resources models to provide the latter, and SDSS allow the integration of both. This is why SDSS are attractive for water resources planning and management. There are several strategies and approaches for the coupling of environmental models with GIS (Nyerges 1993; Fedra 1996), which can range from loose to tight coupling. A *loose coupling* consists in the transfer of data between GIS and numerical models; it is based on two separate systems and, generally, separate data management with transfer of data accomplished by writing and reading ASCII text files. A *tight coupling* is one with integrated data management, in which the GIS and the models share the same database. The tightest of couplings is an embedded or integrated system, in which modeling and data are embedded in a single manipulation framework (Watkins et al. 1996). In the following, several typical coupling methods are discussed.

One way to achieve tight coupling is to use a high-level language or an application generator built into the GIS (Fedra 1996). Keller and Strapp (1996) use an application programming interface (API) to customize commercially available GIS into a specialized SDSS. An API for GIS consists of a library of routines that allows the user to access and integrate most of the functional capacities of the GIS in a standard programming language; this allows the user to write analytical programs, which, through the API functions, directly handle spatial data management, graphic display, and user interaction, instead of using calls in the GIS.

Using an interface to couple models and GIS is often an efficient method, which includes using interface-building tool kits (Djokic and Maidment 1993; Burgin 1995), and using user-defined triggers to customize GIS functionality as well as interface components for simulation models (Lam and Swayne 1991). McKinney, Maidment, and Tanriverdi (1993) propose, and Burgin (1995) implements, an expert information system for Texas water planning, in which expert systems and water resources planning models are used to enhance the modeling capacity of GIS. McKinney and Tsai (1996) use a GIS to create a gridcell-based modeling environment, in which a groundwater flow model is implemented within the GIS. This method was illustrated to be useful for boundary treatment and model construction but was computationally inefficient. Models can be built directly in a GIS (tight coupling) when the model solution requires only sequential solutions of equations. However, when the model requires the simultaneous solution of large numbers of equations, GIS is not efficient.

Object-oriented programming is a very promising method for deep coupling of GIS and environmental models (Yeh 1996; Fedra 1996; Crosbie 1996; Raper and Livingstone 1996). The idea behind this approach is that a river basin is perceived as consisting of objects that interact in specific ways (Crosbie 1996). Object-oriented representation of a river basin includes spatial objects and thematic objects. Spatial objects represent real world entities, and thematic objects include attributes, methods, and topics. Apart from the spatial attributes that can be directly derived from a GIS, there are external physical, environmental, and socioeconomic data related to the spatial objects. Methods are rules or functions describing the relationships between objects. Topics represent tasks or objectives to be completed or reached, which are identified through user interactions. Based on the given attributes, models and GIS functions are understood as methods for topics, and the integration of models and GIS functions becomes the pragmatic question of which method can perform the required task on the selected objects (Fedra 1996). Several applications of object-oriented SDSS have appeared in the water resources literature (Yeh 1996; Reitsma 1996; Fedra and Jamieson 1996; Loucks, French, and Taylor 1996).

Model base management techniques that provide mechanisms for model creating, searching, and coupling can increase the usefulness of SDSS. Bennett, Armstrong, and Weirich (1996) integrate model base management techniques with GIS technology to create a geographic modeling system (GMS), so as to provide users the materials and tools needed to construct and use dynamic geological models.

In summary, SDSS provide unique advantages for water resources management in the following aspects: (1) spatial representation, that is representing the spatial relations of the real world in a visual and analytical form; (2) comprehensive database, which is the basis for the integration of socioeconomic, environmental, and physical components of the real world; and (3) modeling capability, which can integrate simulation/optimization techniques to solve complex water resources management problems. These advantages make SDSS a proactive tool for sustainable water resources management.

Future Directions for River Basin Modeling

Introduction

The review of the literature above makes it clear that the state of the art in river basin modeling has advanced dramatically over the past several years with the rapid improvement in computer hardware and software. However, to be useful in applied empirical policy analysis, river basin models must be designed to provide answers to real-world water policy questions. In this section we introduce an agenda for research on water policy at the river basin level, and describe the appropriate directions for modeling to address this research agenda. Perhaps the most fundamental dilemma facing water policy, particularly in developing countries, is that demand for water for agriculture, household use, and industry continues to increase rapidly, while watersheds, the irrigated land base, and the quality of water delivered to the final user are deteriorating. Scarcity of water has led to demand for policy reform, but many questions concerning feasibility, costs, and likely effects of alternative water allocation policies in developing countries remain unanswered. Despite decreased irrigation investment, irrigated agriculture will be called upon to continue to supply a major share of growth in agricultural output in many regions of the developing world, at the same time that a greater proportion of water will be transferred out of agricultural uses. Water resources policies therefore must be developed to (1) maintain growth in irrigated agricultural production; (2) facilitate efficient inter-sectoral allocation of water, including transfer of water out of agriculture; and (3) reverse the ongoing degradation of the water resources base, including the watershed, irrigated land base, and water quality. Reform of water allocation policies will be increasingly important to meet competing water demands by saving of water in existing uses, to increase the economic benefits from water use, and to improve the quality of water and soils. But the design and the sequencing of appropriate water allocation policy reforms remain poorly understood, and can benefit directly from improved modeling of water allocation at the river basin level.

An appropriate research program must seek to address these issues in ways that will be directly relevant to national governments and international donors for choosing appropriate water policies and establishing priorities for reform of institutions and incentives that affect water resources allocation. Specifically, the research must determine the effectiveness of alternative water allocation mechanisms and seek to understand their productivity, equity, and environmental impacts. On the one hand, the modeling approach adopted must be sufficiently detailed to permit the development of basin-specific solutions requiring on-site empirical modeling. Water management and policy solutions must be tailored to specific countries and regions within countries, because of the great differences in institutional capabilities, irrigation and urban water supply infrastructure, the structure of agriculture, and the degree of water scarcity. Moreover, because of the increasing competition for water, this research must treat water resources allocation in an integrated fashion, considering not only irrigation demands, but also household, industrial, hydropower, and environmental demands. On the other hand, the river basin modeling should be capable of providing a comparative perspective to develop generalizable "best practices" for river basin management under alternative conditions. Thus, the comprehensive analytical modeling framework to be developed should, in its overall structure, be generalizable to other river basins. In the remainder of this section, we summarize some of the key directions for river basin modeling to meet these research objectives.

Integrating Hydrologic-Agronomic-Economic-Institutional Modeling at the River Basin Scale

River basin models must be able to analyze the consequences, both environmental and economic, of water allocation decisions at both the river basin and local (farm and field) scales. Representations of hydrologic processes at scales ranging from single reservoir to multiple reservoir systems, from separate surface water and groundwater systems to conjunctive systems, and from the soil profile to the cropped field, are important precursors to understanding and describing the mass balances at the river basin scale. However, the policy perspective described above needs an integrated basin system to reflect the interrelationships in the real world. It is at the basin level that hydrologic, agronomic, and economic relationships can be integrated into a comprehensive modeling framework and, as a result, policy instruments designed to make more rational economic use of water resources are likely to be applied at this level. An integrated hydrologic-agronomic-economic model at the basin scale will have the following characteristics:

- integration of hydrologic, agronomic, and economic relationships in an endogenous system that will adapt to environmental, ecological, and socioeconomic statuses related to the river basin domain
- specification of an integrated river basin network, on which mathematical models are built, that includes the water supply system (surface water and groundwater), the delivery system (canal network), the water users system (agricultural and nonagricultural), the drainage collection system (surface and subsurface drainage), and the waste water disposal and treatment system, as well as the connections between these subsystems
- representation of the spatial and temporal distribution of water flow and pollutant transport and mass balance through the river basin
- representation of water demands from all water-using sectors for analysis of inter-sectoral water allocation policies
- evaluation of the economic benefits from each of these demands, including crop acreage and crop production functions incorporating both water application and quality
- incorporation of economic incentives for salinity and pollution control, water conservation and irrigation system improvement as policy levers within the model

In such a modeling framework, water use will include not only consumption of water in agricultural and industrial production, but also domestic water use and nonconsumptive water use such as hydropower and ecosystem integrity. The outcomes of water use can then be examined in terms of efficiency, equity, and environmental impact. Over time, these outcomes change the environment through processes such as salinization, siltation, industrial water pollution, technological change, crop diversification and trade, industrialization, migration and population growth, social differentiation, changes in legislation, and institutional change. Much of the analysis of existing water allocation mechanisms can focus on the environment-allocation linkages, while the modeling of impact can deal more with the allocation-use-impact relationships. The prior institutional analysis will contribute to the structure and parameters of the modeling exercise, while results from the impact analysis will help identify emerging stresses and potential avenues for further institutional change.

Currently, a prototype integrated hydrologic-agronomic-economic-institutional model is being developed by a joint research group from the International Food Policy Research Institute (IFPRI), the Center for Research in Water Resources (CRWR) at the University of Texas at Austin, and the International Water Management Institute (IWMI). Based on the on-site empirical research, this model is used for water management policy analysis of the Maipo river basin in Chile. In the analytical framework, the interactions between water allocation, farmer input choice, agricultural productivity, nonagricultural water demand, and resources degradation are formally modeled to estimate the social and economic gains from improvement in the allocation and efficiency of water use. The model provides the description of the underlying physical processes and the institutions and rules that govern the flows of water, salts, and other pollutants through the river basin. It also depicts the demand sites along the river basin, including consumptive use locations for agricultural, municipal, industrial, and in-stream water uses;

and reservoirs and aquifers. Economic benefits to water use are evaluated using production and benefit functions with respect to water for the agricultural, environmental, urban, and industrial sectors. The river basin model is being developed as a user-friendly decision support system integrating the advantages of GIS techniques, describing the water resources system in the real world, into a regional optimization model for water resources allocation. Thus, the modeling framework will serve both as a research tool for policy analysis and as a support system for water authorities.

Comprehensive Information Support

For complex integrated hydrologic-agronomic-economic-institutional modeling, a comprehensive information support is necessary. Multidisciplinary information is an input and also a basis for sustainable water resources management strategy analysis and evaluation. Information for each element in water resources systems, including hydrologic, hydrogeologic, water quality, economic, ecological, and environmental data, with both time-series and spatial distributions and for both the historic records and forecasts for the future, should be collected and treated in an integrated, analytical framework. GIS technology can help achieve comprehensive information support and represent water resources systems in the real world with consideration of spatial dimensions including the geography and topology of the river basin, the functional relationships between various features including the water supply system (surface water and groundwater), the delivery system (canal network), the water user system (agricultural and nonagricultural), the drainage collection system (surface and subsurface drainage), and the wastewater disposal and treatment system. This spatial representation also enables the formulation and analysis of spatial equity among water user groups.

Integrated Short- and Long-Term Models

In the previous sections, several approaches dealing with short-term and long-term modeling have been discussed (for example, Feinerman and Yaron 1983; Lefkoff and Gorelick 1990a,b; Billib et al. 1995). In addition to different time intervals and time horizons, the purpose of these two approaches also differs. The objective of short-term modeling is to search for immediate profits, ignoring the temporal externality (toward the future), while long-term modeling seeks social benefits, considering both spatial and temporal externalities. In addition, long-term modeling can better take account of the accumulative effects of pollutants and of technology advances that will be crucial to future water supply. In a specific time horizon, short-term modeling determines water allocations and quality control each year assuming both the supply and demand conditions are known; whereas, long-term modeling takes account of future uncertainties and the effects of current negative actions. Thus, a combination of short- and long-term modeling with short-term decisions being directed both by short-term objectives and long-term adjustments could help reach long-term optimal decisions, satisfying the immediate demands and desires without compromising those of future years. Thus, in an integrated short- and long-term framework tradeoffs between these differing objectives can be analyzed and potential conflicts between them minimized without compromising the robustness of the water resources system.

Economic, hydrologic, and environmental relationships should be developed for a long time-horizon to simulate long-run accumulative effects, and to reflect potential future changes and uncertainties. These relationships should be based on both theoretical and empirical studies. On the other hand, extending the short-term model into a long-term model with a large number of time periods and more complex structures will lead to complex technical difficulties for mathematical modeling, a direction for future research.

In conclusion, basin-scale water resources management needs the development and use of a systems approach, which is built upon the integrity of a river basin system. This approach should be able to represent geographic information of the basin; combine water quantity and quality management; integrate economic and hydrologic components; and dynamically connect short- and long-term models.

System Integration

An important issue is the system's adaptation to its environment, as defined by everything outside a system boundary. If the system referred to here is treated as the abstraction of a real physical river basin system, then the environment of the system is the socioeconomic status. Water resources systems are adaptive systems since they change corresponding to external socioeconomic changes. The uncertain and unknown economic, social, political, legal, institutional, and organizational changes strongly influence water resources management, and in light of sustainability, a water resources system should be flexible enough to adapt to its dynamic environment. To realize the adaptation, the connection between the water resources physical system and its external socioeconomic system should be implemented in such a way that the physical systems are able to respond and adapt rapidly to the changing economic and social contexts so as to avoid irreversible socioeconomic and environmental losses. This is why integrated economic-hydrologic models have to be holistic tools in basin-scale water resources management.

A river basin is such a complex system that it should be managed in a systematic approach. Much effort has been invested in the modeling of separate components in river basin systems and more effort will be necessary to combine the components into an integral system. It is necessary to understand and appropriately describe the interactions between the various components, as well as their respective behavior. It might be impossible to include the details of each component, but their essential behavior and interrelations should be captured. Interrelations between components might be temporally dynamic, and spatially continuos, depending on different application purposes. Integrated simulation and optimization approaches, including DSS, as reviewed in previous sections, can provide a proactive tool for system integration.

Substantial progress has been made in the development of the tools necessary to support policy makers and river basin authorities in their decisions on efficient, equitable, and sustainable water allocation. The directions for further research suggested above and the application of appropriately designed river basin water allocation models could generate large benefits through improved water policy and water allocation in the river basin. Development and application of appropriate river basin models would assist in (1) the identification of the role and significance of integrated water policy and water management in the process of regional economic growth in the river basin; (2) the assessment of the impact on agricultural production, industrial, and household water use, environmental sustainability, and water quality of alternative institutions, water management, and agricultural policies in the river basin; and (3) the development of a basin-level water management strategy that is consistent with national agricultural and economic development strategies; and that takes into account environmental requirements for water and the impact of agricultural and economic policies and economic growth on water and the environment.

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