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Cover photo: Located in far east Texas and stretching into Louisiana, Caddo Lake is known for its extensive forests of baldcypress trees draped with Spanish moss. This famous lake is home to a rich ecosystem and a wide variety of wildlife. The cover photo was taken during normal water levels, but in 2011 the lake's levels dropped significantly during the drought. Photo credit: Texas Water Resources Institute

Reservoir/River System Management Models

Ralph A. Wurbs¹

Abstract: The U.S. Army Corps of Engineers, Texas Water Development Board, Texas Commission on Environmental Quality, Texas Parks and Wildlife Department, river authorities, regional planning groups, consulting firms, and university researchers model the development, control, allocation, and management of major river systems in Texas in support of a variety of water resources planning and management activities. This paper presents a comparative review of river/reservoir system modeling capabilities that integrates the Texas experience with nationwide endeavors to develop and implement generalized models. The enormous published literature on reservoir/river system models is complex. This state-of-the-art assessment begins with a broad general review of the massive literature and then focuses on generalized modeling systems that have been extensively applied by water management agencies in a broad spectrum of decision-support situations in Texas and elsewhere. Several modeling systems are suggested as being representative of the state-of-the-art from a practical applications perspective. Modeling capabilities are explored from the perspectives of types of applications, computational methods, model development environments, auxiliary analyses, and institutional support. The paper highlights advances in modeling complex river/reservoir system management issues that are significantly contributing to actual practical improvements in water management.

Keywords: reservoir systems, simulation models, water management

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Terms used in paper

Short name or acronym	Descriptive name
AL-V	Surface Water Resources Allocation Model
CADSWES	Center for Advanced Decision Support for Water and Environmental Systems
CALSIM	California Simulation Model
CWMS	Corps Water Management System
DPSIM-I	Dynamic Programming Simulation Model
HEC	Hydrologic Engineering Center
HEC-5	Simulation of Flood Control and Conservation Systems
HEC-DSS	Hydrologic Engineering Center Data Storage System
HEC-FIA	Hydrologic Engineering Center Flood Impact Analysis
HEC-HMS	Hydrologic Engineering Center Hydrologic Modeling System
HEC-PRM	Hydrologic Engineering Center Prescriptive Reservoir Model
HEC-RAS	Hydrologic Engineering Center River Analysis System
HEC-ResSim	Hydrologic Engineering Center Reservoir System Simulation Model
MIKE BASIN	River Basin Simulation Model
MODFLOW	Modular Finite-Difference Flow Model
MODSIM	River Basin Management Decision Support System
MONITOR-I	Surface Storage and Conveyance Systems
OASIS	Operational Analysis and Simulation of Integrated Systems
RiverWare	River and Reservoir Operations Model
SIM-V	Multireservoir Simulation and Optimization Model
SIMYLD-II	River Basin Simulation Model
SUPER	Corps of Engineers Southwestern Division Model
SWD	Corps Southwestern Division
WAM	Water Availability Modeling
WEAP	Water Evaluation and Planning
WRAP	Water Rights Analysis Package
WRESL	Water Resources Engineering Simulation Language
WRIMS	Water Resources Integrated Modeling System

INTRODUCTION

The objectives of this paper are to assist practitioners in selecting and applying models in various types of river/reservoir system management situations and to support research in continuing to improve and expand modeling capabilities. The extensive experience accumulated by the water management community in actually implementing reservoir/river system models differs substantially from the immense published research literature on modeling techniques. Generalized modeling systems play a dominant role in practical applications.

This review of reservoir/river system analysis capabilities focuses on user-oriented generalized modeling systems. *Generalized* means that a model is designed for application to a range of concerns dealing with river systems of various configurations and locations, rather than being site-specific customized to a particular system. Model users develop input datasets for the particular river basin of interest. *User-oriented* implies that a model is designed for use by professional practitioners other than the model developers and is thoroughly tested and well-documented. User-oriented generalized modeling systems should be convenient to obtain, understand, and use and should work correctly, completely, and efficiently.

This state-of-the-art assessment begins with a brief overview of the massive literature, then focuses on the evolution of generalized modeling systems, and finally further focuses on the 4 modeling systems listed in Table 1. Reservoir System Simulation (HEC-ResSim), River and Reservoir Operations (RiverWare), River Basin Management Decision Support System (MODSIM), and Water Rights Analysis Package (WRAP) provide a broad range of analysis capabilities and are representative of the state of the art from the perspective of practical applications dealing with complex river systems. The 4 alternative modeling systems reflect a broad spectrum of types of applications, computational methods, modeling environments, and analysis capabilities.

The U.S. Army Corps of Engineers (Corps) Hydrologic Engineering Center (HEC) has developed a suite of generalized simulation models, including HEC-ResSim, which is extensively applied in Texas as well as nationwide and abroad. The Corps Fort Worth District has routinely applied a model called Southwestern Division Model (SUPER) to the major river basins of Texas over the past several decades and more recently has transitioned to HEC-ResSim and RiverWare. The Lower Colorado River Authority, Lower Neches River Authority, and Tarrant Regional Water District, their consultants, as well as the Corps Fort Worth District have applied RiverWare. MODSIM is based on a network flow programming formulation pioneered in early Texas Water Development Board (Board) river/reservoir system models. WRAP is widely applied by the Board, Texas Commission on Environmental Quality (Commission), Texas Parks and Wildlife Department, regional planning groups, river authorities, and consulting firms. SUPER, HEC-ResSim, RiverWare, MODSIM, and WRAP, and applications thereof, are explored by Wurbs (2005a).

MODELING RIVER SYSTEM DEVELOPMENT AND MANAGEMENT

Computer modeling of reservoir/river systems encompasses various hydrologic, physical infrastructure, environmental, and institutional aspects of river basin development. Dams and appurtenant structures are required to control highly fluctuating river flows to reduce flooding and develop reliable water supplies. Institutional arrangements for allocating and managing water resources are integrally connected to systems of constructed facilities. Management of the water and related land and environmental resources of a river basin integrates natural and man-made systems.

Table 1. Generalized reservoir/river system modeling systems.

Short name	Descriptive name	Model development organization
HEC-ResSim	Hydrologic Engineering Center Reservoir System Simulation	U.S. Army Corps of Engineers Hydrologic Engineering Center http://www.hec.usace.army.mil/
RiverWare	River and Reservoir Operations	Center for Advanced Decision Support for Water and Environmental Systems, U.S. Bureau of Reclamation, Tennessee Valley Authority http://riverware.org/
MODSIM	River Basin Management Decision Support System	Colorado State University and U.S. Bureau of Reclamation http://modsim.engr.colostate.edu/
WRAP	Water Rights Analysis Package	Texas A&M University and Texas Commission on Environmental Quality http://ceprofs.tamu.edu/rwurbs/wrap.htm

The generalized river/reservoir system management models explored in this paper are based on volume-balance accounting procedures for tracking the movement of water through a system of reservoirs and river reaches. The models compute reservoir storage contents, water supply withdrawals, hydroelectric energy generation, and river flows for specified water demands, system operating rules, and input sequences of stream inflows and net reservoir surface evaporation less precipitation rates.

For the water management modeling systems addressed in this paper, the spatial configuration of a river/reservoir system is represented by a set of model control points, sometimes called nodes or stations, connecting river reaches as illustrated in Figure 1. Control points represent the sites of reservoirs; hydroelectric power plants; water supply diversions and return flows; environmental instream flow requirements; conveyance canals and pipelines; stream confluences; river basin outlets; and other system components.

Stream inflows at control points are provided as input. Reservoir storage and streamflows are allocated between water users based on rules specified in the model. The models described in this paper have been applied to river systems ranging in complexity from a single reservoir or run-of-river water supply diversion to river basins containing many hundreds of reservoirs and water supply diversion sites with operations governed by complex multipurpose reservoir system operating rules and institutional water allocation mechanisms.

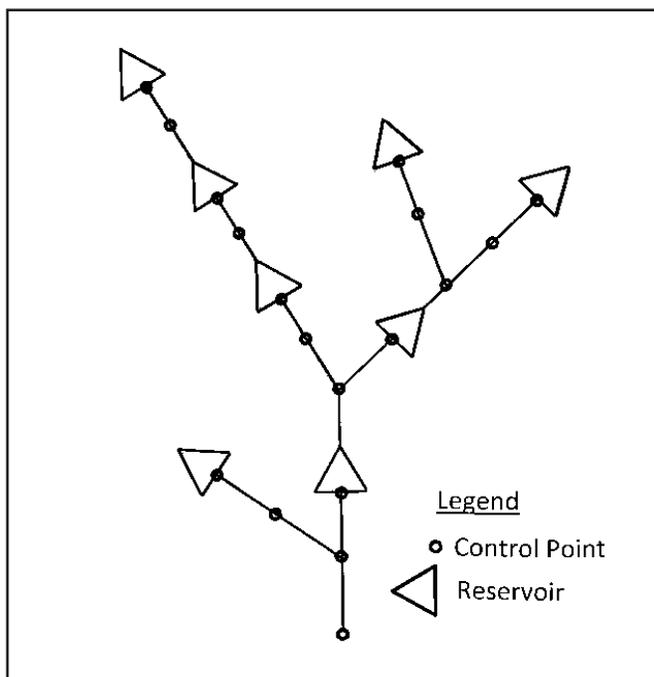


Figure 1. Illustrative schematic of a river system as viewed from a modeling perspective.

These models combine a specified scenario of water resources development, control, allocation, management, and use with a specified condition of river basin hydrology, which is most often historical hydrology representing natural, unregulated conditions. River basin hydrology is represented by stream-flow inflows and net reservoir surface evaporation-precipitation rates for each time step of a hydrologic period-of-analysis.

The hydrologic simulation period and computational time step may vary greatly depending on the application. Storage and flow hydrograph ordinates for a flood event occurring over a few days may be determined at intervals of an hour or less. Water supply capabilities may be modeled with a monthly time step and a many-year hydrologic period-of-analysis, reflecting a full range of fluctuating wet and dry periods, including extended multiyear droughts.

A river/reservoir system model simulates a physical and institutional water management system with specified conditions of water demand for each sequential time step of a hydrologic period-of-analysis. Post-simulation streamflow and reservoir storage frequency analysis and supply reliability analysis capabilities are typically included in the modeling systems addressed by this paper. Reservoir storage and streamflow frequency statistics and water supply reliability metrics are developed for alternative river/reservoir system management strategies and practices.

Other auxiliary modeling features are also, in some cases, incorporated in the river/reservoir management models. Some models include features for economic evaluation of system performance based on cost and benefit relationships expressed as a function of flow and storage. Stream inflows are usually generated outside of the reservoir/river system management model and provided as input to the model. However, reservoir/river system models may also include capabilities for simulating precipitation-runoff processes to generate inflows. Though hydraulics may be pertinent to reservoir operations, separate models of river hydraulics are typically applied to determine flow depths and velocities.

Some reservoir/river system management models simulate water quality constituents along with water quantities. However, generalized water quality models, not covered in this paper, are designed specifically for particular types of river and/or reservoir system water quality analyses. The typically relatively simple water quality features of the models explored in this paper are secondary to their primary function of detailed modeling of water development, regulation, allocation, and management.

Modeling applications often involve a system of several models, utility software products, and databases used in combination. A reservoir/river system management model is itself a modeling system, which often serves as a component of a larger modeling system that may include watershed hydrology and river hydraulics models, water quality models, economic

evaluation tools, statistical analysis methods, databases, and various software tools for managing time series, spatial, and other types of data.

The models discussed here are used for various purposes in a variety of settings. Planning studies may involve proposed construction projects, reallocations of storage capacity, or other operational modifications at existing projects. Reservoir operating policies may be reevaluated periodically to assure responsiveness to current conditions and objectives. Studies may be motivated by drought conditions, major floods, water quality problems, or environmental losses. Operating plans for the next year or next season may be updated routinely based on a modeling system. Models support the administration of treaties, agreements, water rights systems, and other water allocation mechanisms. Real-time modeling applications may involve decision support for water management and use curtailment actions during droughts. Likewise, real-time flood control operations represent another type of application.

RESERVOIR SYSTEM MODELING LITERATURE

Pioneering efforts in computer simulation of reservoir systems in the United States include Corps' studies of 6 reservoirs on the Missouri River initiated in 1953 and International Boundary and Water Commission (Boundary Commission) simulations of the Rio Grande in 1954 (Maass et al. 1966). Major Board model development efforts in support of water planning in Texas began in the 1960s (TWDB 1974). Several books on modeling and analysis of reservoir operations are available (Votruba and Broza 1989; Wurbs 1996; ReVelle 1999; Nagy et al. 2002). Labadie (2004) summarizes the extensive and complex research literature on reservoir system optimization models. Wurbs (1993, 2005a) presents state-of-the-art reviews of reservoir system analysis from a practical applications perspective.

Optimization and Simulation

Reservoir system analysis models have traditionally been categorized as simulation, optimization, or hybrid combinations of both. Development and application of decision-support tools within the federal and state water resources development agencies in the United States have focused on simulation models. The published literature on modeling reservoir systems is dominated by optimization techniques. However, the optimization techniques are often used as the computational engine of simulation models.

The term *optimization* is used synonymously with *mathematical programming* to refer to a mathematical algorithm that computes a set of decision variable values that minimize or maximize an objective function subject to constraints. Optimization

is covered by water resources systems books (Karamouz et al. 2003; Jain and Singh 2003; Simonovic 2009) as well as numerous operations research and mathematics books. Literally thousands of journal and conference papers have been published since the 1960s on applying variations of linear programming, dynamic programming, gradient search algorithms, evolutionary search methods such as genetic algorithms, and other optimization techniques to reservoir system analysis problems. Various probabilistic methods for incorporating the stochastic nature of streamflows and other variables in the optimization models have been proposed (Labadie 2004).

This paper focuses on generalized simulation models. A simulation model is a representation of a system used to predict its behavior under a given set of conditions. Alternative executions of a simulation model are made to analyze the performance of the system under varying conditions, such as for alternative operating plans. Many simulation models incorporate only computational algorithms developed specifically for a particular model. Alternatively, a simulation model may adopt generic algorithms such as linear programming to perform certain computations.

Although optimization and simulation are 2 alternative modeling approaches with different characteristics, the distinction is obscured because models may combine elements of both in various ways. As noted above, optimization algorithms may be embedded within simulation models to perform certain periphery computations or provide the fundamental computational framework for the simulation model. Conversely, an optimization procedure may involve automated iterative executions of a simulation model.

System analysis models are often categorized as being prescriptive or descriptive. Descriptive simulation models demonstrate what will happen if a specified plan is adopted. Prescriptive optimization models automatically determine the plan that will best satisfy specified decision criteria. However, mathematical programming (optimization) techniques are used to perform computations in descriptive simulation models as well as to develop more prescriptive optimization strategies. Although it may be desirable for models to be as prescriptive as possible, real-world complexities of reservoir system operations typically necessitate model orientation toward the more descriptive end of the descriptive/prescriptive spectrum.

Linear Programming

Of the many mathematical programming (optimization) methods available, linear programming, particularly network flow linear programming, has been the method most often adopted in practical modeling applications in support of actual water management activities. The general linear programming formulation described in many mathematics and systems engineering textbooks is as follows:

minimize or maximize	$Z = \sum_{j=1}^n c_j x_j$		(1)
subject to	$\sum a_{ij} x_j \leq b_i$	for $i = 1, \dots, m$ and $j=1, \dots, n$	(2)
	$x_j \geq 0$	for $j = 1, \dots, n$	

A linear programming solution algorithm finds values for the n decision variables x_j that optimize an objective function subject to m constraints. The c_j in the objective function equation and the a_{ij} and b_i in the constraint inequalities are constants.

A number of generalized reservoir system simulation models, including several discussed later in this paper, are based on network flow programming, which is a computationally efficient form of linear programming. Network flow programming is applied to problems that can be formulated in a specified format representing a system as a network of nodes and arcs having certain characteristics. The general form of the formulation is as follows.

minimize or maximize	$\sum \sum c_{ij} q_{ij}$	for all arcs	(4)
subject to	$\sum q_{ij} - \sum q_{ji} = 0$	for all nodes	(5)
	$l_{ij} \leq q_{ij} \leq u_{ij}$	for all arcs	(6)

where q_{ij} is the flow rate in the arc connecting node i to node j ; c_{ij} is a penalty or weighting factor for q_{ij} ; l_{ij} is a lower bound on q_{ij} ; and u_{ij} is an upper bound on q_{ij} .

For a reservoir/river system, the nodes are sites of reservoirs, diversions, stream tributary confluences, and other pertinent system features as illustrated by the control points of Figure 1. Nodes are connected by arcs or links representing the way flow is conveyed. Flow may represent a discharge rate, such as instream flows and diversions, or a change in storage per unit of time.

A solution algorithm determines the values of the flows q_{ij} in each arc that optimize an objective function subject to constraints, including maintaining a mass balance at each node and not violating user-specified upper and lower bounds on the flows. The weighting factors c_{ij} in the objective function are defined in various ways, such as unit costs in dollars or penalty or utility terms, that provide mechanisms for expressing relative priorities. Each arc has 3 parameters: a weighting, penalty, or unit cost factor c_{ij} associated with q_{ij} ; a lower bound l_{ij} on q_{ij} ; and an upper bound u_{ij} on q_{ij} . Network flow programming problems can be solved using conventional linear programming algorithms. However, the network flow format facilitates the use of much more computationally efficient algorithms that allow analysis of large problems with thousands of variables and constraints.

Caution in Applying Simplified Representations of the Real World

Models are necessarily simplified representations of real world systems. Many references discuss shortcomings of the mathematical representations used to model systems of rivers and reservoirs. Rogers and Fiering (1986) outlined institutional and technical reasons that water management practitioners were reluctant to apply formal mathematical optimization algorithms proposed by researchers. These reasons included deficiencies in databases, modeling inadequacies, agency resistance to change, and the fundamental insensitivity of many actual systems to wide variations in design choices. Iich (2009) explored the limitations of network flow programming. McMahon (2009) highlighted the various complexities of applying computer models and concluded that models can be quite useful despite their imperfections when considered in the context of data uncertainties, real-world operator experience, social priorities for water management, and externally imposed constraints on actual operational practice.

Powerful generalized software packages are playing increasingly important roles in water management. Computer models greatly contribute to effective water management. However, models must be applied carefully with professional judgment and good common sense. Model users must have a thorough understanding of the computations performed by the model and the capabilities and limitations of the model in representing the real world.

GENERALIZED RIVER/RESERVOIR SYSTEM MODELS

Many hundreds of reservoir/river system models are described in the published literature. However, only a small number of these models fit the definitions of *generalized* and *user-oriented* presented at the beginning of this paper. Many models are developed for a specific reservoir system rather than being generalized. Most of the numerous reservoir system optimization models reported in the literature were developed in university research studies and have not been applied by model users other than the original model developers.

Under the sponsorship of the Corps Institute for Water Resources, Wurbs (1994, 1995) inventoried generalized water management models in the categories of demand forecasting, water distribution systems, groundwater, watershed runoff, stream hydraulics, river and reservoir water quality, and reservoir/river system operations. Wurbs (2005a) reviewed generalized reservoir/river system operations models in greater detail for the Corps Fort Worth District. Most of the models cited in these inventories were developed by government agencies in the United States and are in the public domain, meaning they

are available to interested model users without charge.

Public domain generalized modeling systems play important roles in many aspects of water management in the United States (Wurbs 1998). Of the many water-related models used in the United States, the Hydrologic Modeling System (HEC-HMS) and River Analysis System (HEC-RAS) are probably applied most extensively. These and other models developed by the Corps Hydrologic Engineering Center are available at the website shown in Table 1. HEC-HMS watershed precipitation-runoff and HEC-RAS river hydraulics modeling are combined with HEC-ResSim in the integrated Corps Water Management System for modeling reservoir system operations as described later. However, most applications of HEC-HMS and HEC-RAS by government agencies and consulting firms are for urban floodplain delineation or design of urban stormwater management facilities. The number of agencies and individuals that model operations of major multipurpose reservoir systems is much smaller than the number of users of HEC-HMS, HEC-RAS, and various other generalized models used for other purposes. However, generalized reservoir system models are significantly contributing to effective river basin management.

A Hydrologic Modeling Inventory is maintained at Texas A&M University in collaboration with the U.S. Bureau of Reclamation (Bureau) at <http://hydrologicmodels.tamu.edu/>. The inventory is updated periodically, including an update during 2010. Models are organized in various categories with summary descriptions provided for each model. The inventory includes the MIKE BASIN (River Basin Simulation Model), California Simulation Model (CALSIM), MODSIM, RiverWare, and WRAP models cited later in this paper. In addition to developing and maintaining the Hydrologic Modeling Inventory, Singh and Frevert (2006) edited a book inventorying models focused primarily on generalized models of watershed hydrology but also several river/reservoir system management models, including RiverWare (Zagona et al. 2006), MODSIM (Labadie 2006), and WRAP (Wurbs 2006).

The following review focuses on several of the generalized reservoir/river management modeling systems extensively applied by water management agencies and/or their consultants to support actual planning and/or operations decisions. The models cited below along with other similar models are discussed in more detail by Wurbs (2005a).

Early Models Developed by the Texas Water Development Board

The Board has adopted the WRAP modeling system, described later, for statewide and regional planning studies conducted in recent years (TWDB 2012). WRAP supports both the water rights system administered by the Commission and the planning activities led by the water board. However,

the water board has developed a number of other generalized models in the past.

The Board began development of a series of models in the 1960s in conjunction with formulation of the Texas Water Plan. Several generalized models, reflecting pioneering applications of network flow programming formulations of river/reservoir systems, evolved through various versions. River Basin Simulation Model (SIMYLD-II), Surface Water Resources Allocation Model (AL-V), and Multireservoir Simulation and Optimization Model (SIM-V) (Martin 1983) incorporate a capacitated network flow formulation, presented earlier in this paper, solved with the out-of-kilter linear programming algorithm described by Jensen and Barnes (1980).

SIMYLD-II provides capabilities for analyzing water storage and transfer within a multireservoir or multibasin system with the objective of meeting a set of specified demands in a given order of priority (TWDB 1974). If sufficient water is not available to meet competing demands during a particular time interval, the shortage is assigned to the lowest priority demand node. SIMYLD-II also determines the firm yield of a single reservoir within a multireservoir system. An iterative procedure is used to adjust the demands at a reservoir in order to converge on its firm yield.

The AL-V and SIM-V simulate and optimize the operation of an interconnected system of reservoirs, hydroelectric power plants, pump canals, pipelines, and river reaches (Martin 1983). Martin (1987) describes the Surface Storage and Conveyance Systems (MONITOR-I) model developed by the Board to analyze complex surface water storage and conveyance systems operated for hydroelectric power, water supply, and low flow augmentation. These linear programming models use an iterative successive linear programming algorithm to handle nonlinearities associated with hydroelectric power and other features of the model. The decision variables are daily reservoir releases, water diversions, and pipeline and canal flows. The objective function to be maximized is an expression of net economic benefits.

Martin (1987) incorporated a dynamic programming algorithm in a modeling procedure for determining an optimal expansion plan for a water supply system. The optimization procedure determines the least-costly sizing, sequencing, and operation of storage and conveyance facilities over a specified set of staging periods. This Board dynamic programming-based model, called Dynamic Programming Simulation Model (DPSIM-I), was combined with the previously AL-V and SIM-V models described above.

These early Board models, the original California Department of Water Resources model cited in the next paragraph, and the original versions of HEC-Prescriptive Reservoir Model (PRM) and MODSIM discussed later are all based on the same network flow programming solution algorithm originally developed for the Board models. An early version

of WRAP was also developed using the same algorithm, but another simulation approach was actually adopted for WRAP (Wurbs and Yerramreddy 1994). The original solution algorithms in HEC-PRM and MODSIM were later replaced with much more computationally efficient network flow programming algorithms.

Models Developed by the California Department of Water Resources

CALSIM consists of the generalized Water Resources Integrated Modeling System (WRIMS) combined with input datasets for the interconnected California State Water Project and federal Central Valley Project. The California Department of Water Resources in partnership with the Bureau developed the WRIMS and CALSIM modeling system (Draper et al. 2004) to replace an earlier California Department of Water Resources model (Chung and Helweg 1985), which was based on the network flow programming algorithm developed for the water board models described above.

The generalized WRIMS and CALSIM are designed for evaluating operational alternatives for large, complex river systems. The modeling system integrates a simulation language for defining operating criteria, a linear programming solver, and graphics capabilities. The monthly time step simulation model is based on a linear programming formulation that minimizes shortages in supplying delivery and storage targets with different priorities assigned to different targets. Adjustment computations are performed after the linear programming solution each month to deal with nonlinear aspects of modeling complex system operations. A feature called the Water Resources Engineering Simulation Language (WRESL) was developed for the model to allow the user to express reservoir/river system operating requirements and constraints. Time series data are stored using the HEC-Data Storage System (DSS) (HEC-DSS; 1995, 2009), which is also used with HEC-ResSim and WRAP as well as other HEC simulation models. HEC-DSS provides capabilities for plotting graphs and performing arithmetic operations and statistical analyses.

Models Developed by Federal Agencies

Most of the large federal reservoirs in the United States were constructed and are operated by the Corps or the Bureau. The Corps has more than 500 reservoirs in operation across the nation and plays a dominant role in operating large reservoir systems for navigation and flood control (Johnson and Dibuno 1994). The Bureau operates about 130 reservoirs in the 17 western states (USBR 1992). The Bureau water development program was originally founded upon constructing irrigation projects to support development of the western United States. The responsibilities of the 2 agencies evolved over time

to emphasize comprehensive multipurpose water resources management.

The Bureau has constructed 5 reservoirs in Texas (Lakes Travis, Twin Buttes, Texana, Choke Canyon, and Meredith), but these projects are now owned and operated by nonfederal agencies. The Corps Galveston District owns and operates the Addicks and Barker flood control dams in Houston. The Corps Tulsa District owns and operates Lakes Texoma, Pat Mayse, and Truscott in the Red River Basin. The Fort Worth District owns and operates 25 multipurpose reservoirs located in several Texas river basins. The total of 30 Corps reservoirs account for about 3% of the conservation storage capacity and 75% of the flood control capacity of the 190 major reservoirs in Texas containing 5,000 acre-feet or more storage capacity. International Falcon and Amistad reservoirs on the Rio Grande are owned and operated by the Boundary Commission and contain 14% of both the conservation and flood control capacity of the 190 major Texas reservoirs (Wurbs 1987; TWDB 2011).

The Corps and the Bureau developed many models for specific reservoir systems located throughout the United States during the 1950s–1970s (Wurbs 1996, 2005a). Many of these system-specific models have since been replaced with generalized models. The bureau currently uses MODSIM and RiverWare, described later, and several remaining system-specific models. Generalized Corps models are noted as follows, and HEC-ResSim is described in more detail later in this paper.

Corps of Engineers Generalized Modeling Systems

The Corps Hydrologic Engineering Center maintains a suite of generalized simulation models that are widely applied by water agencies, consulting firms, and universities throughout the United States and the world as well as within the Corps. The different HEC models deal with watershed hydrology, river hydraulics, flood economics, water quality, and statistical analysis, as well as river/reservoir system operations.

The Corps Water Management System (CWMS) is the automated information system used by the Corps nationwide to support real-time operations of flood control, navigation, and multipurpose reservoir systems (Fritz et al. 2002). The Fort Worth and Tulsa Districts are responsible for implementing the CWMS in Texas. The CWMS is an integrated system of hardware and software that compiles and processes hydro-meteorology, watershed, and project status data in real-time. A map-based user interface facilitates modeling and evaluation of river/reservoir system operations. CorpsView, a spatial visualization tool developed by the Corps Hydrologic Engineering Center, based on commercially available geographic information system software, provides a direct interface to geographic information system products and associated attribute information. The CWMS combines data acquisition/management

tools with simulation models, which include HEC-HMS, HEC-ResSim, HEC-RAS, and HEC-Flood Impact Analysis (FIA) (Fritz et al. 2002).

The Lower Colorado River Authority of Texas was the first non-Corps agency to adopt the integrated CWMS (Ickert and Luna 2004) and has used the CWMS to model flood control operations of the Lower Colorado River Authority reservoir system. The component generalized simulation modeling systems (HEC-HMS, HEC-RAS, HEC-ResSim, and HEC-FIA) incorporated in the CWMS are widely applied by various entities in Texas, like elsewhere, as separate individual models.

The HEC-5 Simulation of Flood Control and Conservation Systems model (HEC 1998) has been used since the 1970s in many Corps and non-Corps studies, including studies of river basins in Texas, which have included investigations of storage reallocations and other operational modifications at existing reservoirs, feasibility studies for proposed new projects, and support of real-time operations. The HEC plans to eventually replace HEC-5 with HEC-ResSim (HEC 2007). HEC-5 is no longer in development or supported but is still available at the HEC website (Table 1) and continues to be applied by various model users.

HEC-5 simulates the operation of multipurpose reservoir systems for inputted sequences of unregulated streamflows and reservoir evaporation rates using a variable time interval. A monthly or weekly computational time step may be used during periods of normal or low flows in combination with a daily or hourly time step during flood events. HEC-5 makes release decisions to empty flood control pools and to meet user-specified diversion and instream flow targets based on reservoir storage levels and streamflows at downstream locations. Flood routing options include modified Puls, Muskingum, working R&D, and average lag. Optional analysis capabilities include computation of expected annual flood damages and water supply firm yields.

The HEC-PRM was developed in conjunction with studies of reservoir systems in the Missouri and Columbia river basins. Later applications include studies of systems in California, Florida, and Panama (Draper et al. 2003; Watkins et al. 2004). HEC-PRM is a network flow programming model designed for prescriptive applications involving minimization of a cost-based objective function. *Prescriptive* implies that the model automatically determines the best plan, as contrasted with *descriptive* models that demonstrate what will happen if a specified plan is adopted. Reservoir release decisions are made based on minimizing costs associated with convex piecewise linear penalty functions associated with various purposes, including hydroelectric power, recreation, water supply, navigation, and flood control. Schemes have also been devised to include noneconomic components in the objective function. HEC-PRM applications to date have used a monthly time interval.

The Corps has applied HEC-5, HEC-ResSim, and most recently RiverWare, to most or all of the major river basins of Texas. However, in the past Corps applied the SUPER model most extensively in Texas. Applications of SUPER as well as HEC-5, HEC-ResSim, and RiverWare have included multipurpose reservoir system operations but have focused on flood control (Wurbs 2005a).

The Corps' Southwestern Division developed the SUPER model, and the Division office in Dallas and the Fort Worth, Tulsa, and Little Rock District offices of the Southwestern Division have applied the model (Hula 1981). The model is generalized for application to any river basin but is designed for application within the Corps. SUPER is maintained and continues to be applied by the Fort Worth District but is being phased out and replaced with RiverWare (Avance et al. 2010). SUPER simulates the daily sequential regulation of a multipurpose system of reservoirs and the corresponding hydrologic and economic impacts.

Models Developed by International Research and Consulting Organizations

The Danish Hydraulic Institute (<http://www.dhi.dk/>) has developed a suite of models dealing with various aspects of hydraulics, hydrology, and water resources management. MIKE BASIN, the reservoir/river system component of the Danish Hydraulic Institute family of software, integrates geographic information system capabilities with modeling river basin management. MIKE BASIN simulates multipurpose, multireservoir systems based on a network formulation of nodes and branches. Time series of monthly inflows to the stream system are provided as input. Various options are provided for specifying reservoir operating rules and allocating water between water users.

The Water Evaluation and Planning System developed by the Stockholm Environmental Institute (<http://www.weap21.org/>) is a reservoir/river/use system water balance accounting model that allocates water from surface water and groundwater sources to different types of demands. The modeling system is designed as a tool for maintaining water balance databases, generating water management scenarios, and performing policy analyses.

The Operational Analysis and Simulation of Integrated Systems (OASIS) model developed by HydroLogics, Inc. (<http://www.hydrologics.net/>) is based on linear programming. Reservoir operating rules are expressed as goals and constraints defined by the model user, using a patented scripting language that is similar to the WRESL in the WRIMS-CALSIM discussed earlier.

SELECTED STATE-OF-THE-ART GENERALIZED MODELING SYSTEMS

The 4 user-oriented generalized modeling systems in Table 1 have been adopted for the following, more focused review of capabilities for modeling river system development and management. HEC-ResSim, RiverWare, MODSIM, and WRAP provide comprehensive capabilities for a broad spectrum of river/reservoir system management decision-support applications. They are distinctly different from each other. However, as a group, the 4 alternative modeling systems are representative of the current state-of-the-art of professional practice in the United States in analyzing complex river/reservoir system water management problems.

All 4 of the modeling systems have been applied in Texas and in other countries. WRAP has been used extensively in Texas. HEC-ResSim, MODSIM, and RiverWare have been used extensively in other states in the United States.

The 4 modeling systems were developed and are maintained by water agencies and university researchers specifically for application by model users other than the original developers and are accessible to water management professionals throughout the world. The HEC-ResSim, MODSIM, and WRAP software and documentation can be downloaded free-of-charge at the websites listed in Table 1. RiverWare is a proprietary software product, which is available for a licensing fee as described at the website shown in Table 1. The 4 software packages all run on personal computers operating under Microsoft Windows, and all have also been executed with other computer systems as well. RiverWare was developed primarily for Unix workstations though it also is used on personal computers with Microsoft Windows.

The 4 alternative modeling systems and their predecessors have evolved through multiple versions over 20 or more years of research and development, with new versions being released periodically. The modeling capabilities provided by each of the models have changed significantly over time and continue to be improved and expanded.

Hydrologic Engineering Center Reservoir Simulation Model

The Corps Hydrologic Engineering Center initiated development of HEC-ResSim in 1996. HEC-ResSim was first released to the public in 2003 with the intention of eventually replacing HEC-5, which has been extensively applied for more than 30 years. Documentation consists of an Users Manual (HEC 2007) and other information found at the website in Table 1. HEC-ResSim is designed for application either independently of the previously discussed CWMS or as a component thereof.

HEC-ResSim is comprised of a graphical user interface, a computational program to simulate reservoir operation, data management capabilities, and graphics and reporting features. Multipurpose, multireservoir systems are simulated using algorithms developed specifically for the model rather than formal mathematical programming (optimization) methods such as linear programming. Meeting the needs of Corps reservoir control personnel for real-time decision support has been a governing objective in developing HEC-ResSim. The model is also applicable in planning studies. The full spectrum of multipurpose reservoir system operations can be modeled with particularly detailed capabilities provided for modeling flood control operations.

Computations are proceeded by control points generally in an upstream-to-downstream sequence. The user-selected computational time step may vary from 15 minutes to one day. Streamflow routing options include Muskingum, Muskingum-Cunge, modified Puls, and other methods. Streamflow hydrographs provided as input to HEC-ResSim can come from any source, including being generated with the HEC-HMS. Multireservoir systems, with each reservoir having multiple outlet structures, can be modeled. Release decisions are based on specified storage zones defined by elevation and a set of rules that specify the goals and constraints governing releases when the storage level falls within each zone.

RiverWare Reservoir and River Operation Modeling System

The Bureau and Tennessee Valley Authority jointly sponsored development of RiverWare at the Center for Advanced Decision Support for Water and Environmental Systems of the University of Colorado (Zagona et al. 2001; Zagona et al. 2006). RiverWare development efforts date back to the mid-1990s, building on earlier modeling systems developed at the Center for Advanced Decision Support for Water and Environmental Systems that extend back to the mid-1980s. The Corps Fort Worth District recently sponsored addition of flood control features to RiverWare (Avance et al. 2010).

RiverWare provides the model user with a kit of software tools for constructing a model for a particular river/reservoir system and then running the model. The model-building tools include a library of modeling algorithms, solvers, and a language for coding operating policies. The tools are applied within a point-and-click graphical user interface. RiverWare routes inflows, provided as input, through a system of reservoirs and river reaches. The primary processes modeled are volume balances at reservoirs, hydrologic routing in river reaches, evaporation and other losses, diversions, and return flows. Optional features are also provided for modeling groundwater interactions, water quality, and electric power economics.

Computational algorithms for modeling reservoir/river system operations are based on 3 alternative approaches: (1) pure simulation, (2) rule-based simulation, and (3) optimization combining linear programming with preemptive goal programming. Pure simulation solves a uniquely and completely specified problem. In rule-based simulation, certain information is generated by prioritized policy rules specified by the model user. Preemptive goal programming considers multiple prioritized objectives based on multiple linear programming solutions (Eschenbach et al. 2001). As additional goals are considered, the optimal solution of a higher priority goal is not sacrificed to optimize a lower priority goal.

The Tennessee Valley Authority applies RiverWare in optimizing the daily and hourly operation of the system of multipurpose reservoirs and hydroelectric power plants. The Bureau has used RiverWare as a long-term planning model and mid-term operations model of the Colorado River as well as a daily operations model for both the Upper and Lower Colorado Regions. The Bureau has also applied the model in the Rio Grande, Yakima, and Truckee river basins. The Lower Colorado River Authority has applied RiverWare in daily time step modeling of water supply operations of the 6 Lower Colorado River Authority reservoirs on the Colorado River of Texas (Zagona et al. 2010). The Tarrant Regional Water District in the upper Trinity River Basin of Texas, Lower Neches River Authority of Texas, and Corps Fort Worth District are included among the other entities that have applied RiverWare to various river basins in the western and southwestern United States (Avance et al. 2010).

MODSIM River Basin Management Decision Support System

MODSIM is a general purpose reservoir/river system simulation model based on network flow linear programming developed at Colorado State University (Labadie 2006; Labadie and Larson 2007). The model has evolved through many versions, with initial development dating back to the 1970s. The Bureau has been a primary sponsor of continued model improvements at Colorado State University. University researchers in collaboration with various local, regional, and international water management agencies have applied MODSIM in studies of a number of reservoir/river systems in the western United States and throughout the world. The software, users manual, tutorials, and papers describing various applications are provided at the website in Table 1.

MODSIM provides a graphical user interface and a general framework for modeling. A river/reservoir system is defined as a network of nodes and links. The objective function (Equation 4) consists of the summation over all links in the network of the flow in each link multiplied by a priority or cost coefficient.

The objective function coefficients are factors entered by the model user to specify relative priorities that govern operating decisions. The coefficients could be unit monetary costs or more typically numbers without physical significance other than simply reflecting relative operational priorities. An iterative algorithm deals with nonlinearities such as evaporation and hydropower computations in the linear programming model. The linear programming problem is solved for each individual time interval without considering future inflows and future decisions.

Monthly, weekly, or daily time steps may be adopted for long-term planning, medium-term management, and short-term operations. A lag flow routing methodology is used with a daily time step. The user assigns relative priorities for meeting diversion, instream flow, hydroelectric power, and storage targets, as well as lower and upper bounds on the flows and storages computed by the model. Optional capabilities are also provided for simulating salinity and conjunctive use of surface water and groundwater.

Water Rights Analysis Package Modeling System

Development of WRAP at Texas A&M University began in the late 1980s sponsored by a cooperative research program of the U.S. Department of the Interior and Texas Water Resources Institute. WRAP has been greatly expanded since 1997 under the auspices of the Commission in conjunction with implementing a statewide Water Availability Modeling (WAM) System (Wurbs 2005b). The Board, Texas Water Resources Institute, the Corps Fort Worth District, and other agencies have also sponsored improvements to WRAP. The software and documentation (Wurbs 2009, 2011a, 2011b, 2011c; Wurbs and Hoffpauir 2011) are available at the website in Table 1.

WRAP is generalized for application to river/reservoir systems located anywhere in the world, with model users developing input datasets for the particular river basins of concern. For studies in Texas, the publicly available WAM System datasets can be altered as appropriate to reflect proposed water management plans of interest, which could involve changes in water use or reservoir/river system operating practices, construction of new facilities, or other water management strategies. The Commission's WAM System consists of the generalized WRAP along with input datasets for the 23 river basins of Texas that include naturalized streamflows at about 500 gaged sites, watershed parameters for distribution of these flows to more than 12,000 ungaged locations, 3,450 reservoirs, water use requirements associated with about 8,000 water rights permits reflecting 2 different water rights systems, 2 international treaties, and 5 interstate compacts.

WRAP simulates water resources development, manage-

ment, regulation, and use in a river basin or multibasin region under a priority-based water allocation system. In WRAP terminology, a water right is a set of water use requirements, reservoir storage and conveyance facilities, operating rules, and institutional arrangements for managing water resources. Streamflow and reservoir storage are allocated among users based on specified priorities, which can be defined in various ways. Simulation results are organized in optional formats, including entire time sequences, summaries, water budgets, frequency relationships, and various types of reliability indices. Simulation results may be stored as DSS files accessed with HEC-DSSVue (a program used to manipulate data from HEC-DSS databases) for plotting and other analyses (HEC 1995, 2009).

The WRAP/WAM System is applied by water rights permit applicants in assessing reliabilities of proposed water management/use strategies and projects and the impacts on other water users. The Commission staff use the modeling system to evaluate permit applications. The board, regional planning groups, and the planning groups' consultants apply the modeling system in regional and statewide planning studies. River authorities and other water management entities also apply WRAP for various internal planning and management purposes.

WRAP modeling capabilities that have been routinely applied in the Texas WAM System consist of using a hydrologic period-of-analysis of about 60 years and a monthly computational time step to perform water availability and reliability analyses for municipal, industrial, and agricultural water supply; environmental instream flow; hydroelectric power generation; and reservoir storage requirements (Wurbs 2011a, 2011b, 2011c). Recently developed additional WRAP modeling capabilities include: short-term conditional reliability modeling; daily time step modeling capabilities that include flow forecasting and routing methods and disaggregation of monthly flows to daily; simulation of flood control reservoir system operations; and salinity simulation (Wurbs 2009, Wurbs and Hoffpauir 2011, Wurbs et al. 2012).

COMPARATIVE SUMMARY OF MODELING CAPABILITIES

HEC-ResSim, RiverWare, MODSIM, WRAP, and other similar models provide flexible capabilities for analyzing multipurpose river/reservoir system operations. The models are water accounting systems that compute reservoir storages and releases and streamflows for each time step of a specified hydrologic period-of-analysis for a particular scenario of water resources development, management, allocation, and use. Though fundamentally similar, the 4 modeling systems differ significantly in their organizational structure, computational algorithms, user interfaces, and data management mechanisms. The alternative modeling systems provide general frameworks for constructing and applying models for specific systems of reservoirs and river reaches. Each of the generalized modeling systems is based upon its own set of modeling strategies and methods and has its own terminology or modeling language.

Types of Applications

Water development purposes are a key consideration in formulating a modeling approach. The distinction between flood control and conservation purposes such as hydroelectric power and water supply is particularly important. Hydrologic analyses of floods focus on storm events, and analyses of droughts are long-term time series oriented. Modeling flow attenuation is important for flood control. Evaporation is important for conservation operations. Flood control operations are typically modeled using a daily or smaller time step. Modeling of conservation operations is sometimes based on a daily interval, but monthly or weekly time steps are more common.

All 4 of the alternative modeling systems are designed to simulate flood control, hydropower, water supply, environmental flows, and other reservoir management purposes. However, whereas development of the other 3 models was motivated primarily by conservation purposes, HEC-ResSim

Table 2. Alternative development frameworks.

Modeling system	Programming language	Computational approach	Computational time step
HEC-ResSim	Java	ad hoc	15 minutes to day
RiverWare	C++	ad hoc and LP	hour to year
MODSIM	C++.NET, Basic.NET	network LP	month, week, day
WRAP	Fortran	ad hoc	month, day, other

is flood control oriented. HEC-ResSim is limited to daily or shorter time steps and provides greater flexibility for flood routing and simulating flood control operations. RiverWare and WRAP have been recently expanded to increase their flexibility for modeling flood control.

In addition to the basic water accounting computations, the modeling systems include various optional features for reliability and frequency analyses, economic evaluations, water quality, and surface/groundwater interactions. These features may involve either computations performed during the simulation or additional post-simulation computations performed using simulation results. WRAP has particularly comprehensive options for reliability and frequency analyses. The relative priorities represented by the objective function coefficients in MODSIM and the RiverWare linear programming option may optionally be economic costs or benefits. MODSIM and WRAP simulate salinity. RiverWare options include various water quality constituents.

These surface water models have no capabilities for detailed modeling of groundwater. However, groundwater sources and channel losses are included in each of the 4 models. Surface water and groundwater interactions have been approximated in various ways. MODSIM and RiverWare have been linked with the U.S. Geological Survey Modular Finite-Difference Flow Model (MODFLOW) groundwater model. The development board has investigated approaches for linking WRAP-based surface water availability models and MODFLOW-based groundwater availability models (HDR 2007).

As noted earlier in this paper, models can be categorized as being prescriptive or descriptive. HEC-ResSim and WRAP are purely descriptive simulation models. MODSIM and RiverWare are basically descriptive simulation models but include features that facilitate a more prescriptive orientation. MODSIM is based on a network flow optimization formulation. RiverWare includes an optional goal programming feature.

Computational Structure

The term *ad hoc* in Table 2 refers to computational strategies developed specifically for a particular model, as contrasted with linear programming, which is a generic algorithm incorporated in numerous models. HEC-ResSim and WRAP are organized based upon ad hoc model-specific computational frameworks. MODSIM is based on network flow linear programming. RiverWare has 2 alternative solution options based on ad hoc algorithms and a third option that uses linear programming. The linear programming-based models have additional ad hoc computational algorithms used along with their linear programming solver, but the linear programming solver accounts for a major portion of the computations.

Repetitive loops and iterative solution procedures are incorporated in all of the models. Iterative algorithms are required

for evaporation and hydropower computations. Evaporation depends upon end-of-period storage, but end-of-period storage depends upon evaporation. Reservoir storage volume versus surface area and elevation relationships are nonlinear. In the linear programming models, the entire linear programming solution of the whole system is repeated iteratively. With the ad hoc simulation procedures, the computations for an individual reservoir are repeated iteratively.

HEC-ResSim and RiverWare generally follow an upstream-to-downstream progression in considering requirements for reservoir storage and releases, diversions, and hydropower generation. WRAP and MODSIM simulation computations are governed by user-specified priorities in considering water management requirements. The WRAP and MODSIM priority-based frameworks are beneficial in modeling complex water allocation systems.

RiverWare includes an optional prescriptive optimization feature that combines linear programming and goal programming. Computations are performed simultaneously for all the time intervals. Thus, model results show a set of reservoir storages and releases that minimize or maximize a defined objective function, assuming all future streamflows, known as release decisions, are made simultaneously during each period. The HEC-PRM and many other optimization models reported in the research literature also adopt this approach of optimizing an objective function while simultaneously considering all time steps of the entire period-of-analysis. Since the future is not known in the real world, these models reflecting knowledge of the future provide an upper-limit scenario on what can be achieved. With the exception of options for short-term flow forecasting, HEC-ResSim, MODSIM, WRAP, and the simulation options in RiverWare step through time-performing computations at each individual time step. Thus, operating decisions are not affected by future inflows and future operating decisions.

Modeling Environment and Interface Features

A model for a particular reservoir/river system consists of a generalized modeling system and an input dataset describing the reservoir/river system. The generalized modeling system provides an environment or framework for assembling input data, executing the simulation computations, and organizing, analyzing, and displaying results.

Each of the 4 modeling systems has its own unique framework within which the user constructs and implements a model for a particular reservoir/river system. With HEC-ResSim, various elements provided by watershed setup, reservoir network, and simulation modules are used to construct and execute a model. MODSIM is based on network flow programming with a reservoir/river system represented by a network of nodes and links with information compiled through an object-oriented interface. WRAP is about managing pro-

grams, files, input records, and results tables, with water management and use practices being described in the terminology of water rights. RiverWare has an object/slot-based environment for building models within the context of object-oriented programming and provides 3 optional solutions.

The user interfaces of the alternative models reflect both similarities and significant differences. HEC-ResSim, RiverWare, and MODSIM provide sophisticated graphical user interfaces with menu-driven editors for entering and revising input data and displaying simulation results in tables and graphs. They also have features allowing a river/reservoir system schematic to be created by selecting and connecting icons. WRAP has a simple user interface for managing programs and files, which relies upon standard Microsoft Office programs for entering, editing, and displaying data. WRAP as well as HEC-ResSim connect with and rely upon graphics capabilities of the HEC-DSS. Geographic information system tools are included in all 4 of the modeling systems.

The compiled executable software products were developed in the programming languages shown in Table 2. HEC-ResSim, MODSIM, and RiverWare also have their own simulation rule language to allow users to express reservoir/river system operating requirements as a series of statements with if-then-else and similar constructs.

Data management efficiency, effective communication of results, documentation, and ease-of-use are important factors in applying a modeling system. Documentation includes both instructions for using the software and detailed technical documentation for understanding modeling methods. The software should be as near error-free as possible; assuming error-free software may be an idealistic goal yet to be achieved. Dealing with errors introduced by users in model input data is important. Therefore, the modeling systems contain various mechanisms for detecting and correcting blunders and inconsistencies in input data.

The organizations and individuals who originally developed the 4 modeling systems continue to improve the models and support their application. HEC-ResSim, MODSIM, and WRAP software and manuals are available free-of-charge at the websites listed in Table 1. Licensing fees and training required to implement RiverWare are described at its website. RiverWare is designed for Unix workstations but is also used on personal computers with Microsoft Windows. The other 3 modeling systems are usually executed on personal computers with Microsoft Windows but can be applied with other computer systems as well.

CONCLUSIONS

The evolution of computer modeling of systems of rivers and reservoirs that began in the 1950s is still underway and is expected to continue. Modeling systems continue to grow in

response to advances in computer technology and intensifying water management and associated decision-support needs. The published literature on modeling reservoir systems is massive and complex and is focused largely on mathematical optimization methods. Generalized modeling systems dominate practical applications. HEC-ResSim, RiverWare, MODSIM, WRAP, and other similar models, though continually improved and expanded, are well established and significantly contributing to water management in Texas as well as throughout the United States and the world.

Generalized modeling systems reflect the types of applications that motivated their development. HEC-ResSim serves as the reservoir system operations component of the CWMS implemented in the Corps district offices nationwide to support real-time operations of multipurpose reservoirs and flood control and navigation projects. HEC-ResSim is also used in planning studies. RiverWare was developed as a partnership between Center for Advanced Decision Support for Water and Environmental Systems, the Bureau, and the Tennessee Valley Authority. The Tennessee Valley Authority uses HEC-ResSim to support real-time hydroelectric power system operations within the setting of multipurpose reservoir system operations. The Bureau applies RiverWare for both long-term planning and short-term operational planning for its multipurpose reservoir systems. The network flow programming-based MODSIM was developed at Colorado State University in collaboration with the Bureau and has been applied in studies both in the United States and abroad. WRAP supports statewide and regional planning and water rights regulatory activities in Texas that require detailed modeling of diverse and complex institutional water allocation arrangements and reservoir/river system management practices.

HEC-ResSim, RiverWare, MODSIM, and WRAP provide general frameworks for constructing and applying models for specific systems of reservoirs and river reaches. Each of these 4 generalized modeling systems is based upon its own set of data management and computational techniques and has its own modeling terminology or language structure, but they all provide flexible broad-based generic capabilities for modeling and analysis of river system development and management.

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