

Generalized Models of River System Development and Management

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1. Introduction

This comparative review of capabilities for computer simulation of the control, allocation, and management of the water resources of river basins focuses on user-oriented generalized modeling systems developed in the United States that are applicable anywhere in the world. The objectives of this chapter 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 chapter begins with a broad general review of the massive literature and then focuses on comparing several generalized modeling systems that have been extensively applied by water management agencies in a broad spectrum of decision-support situations. Modeling capabilities are explored from the perspectives of computational methods, model development environments, applications, auxiliary analyses, and institutional support. The chapter highlights advances in modeling complex issues in managing rivers and reservoirs that are significantly contributing to actual practical improvements in water management.

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

This review of computer modeling of river system development and management focuses on user-oriented generalized modeling systems developed in the United States. *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 extensive literature and then focuses on the four modeling systems listed in Table 1. ResSim, MODSIM, WRAP, and RiverWare were developed and are extensively applied in the United States, are also applied in other countries, 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 four alternative modeling systems reflect a broad spectrum of computational methods, modeling environments, and analysis capabilities.

Short Name	Descriptive Name	Model Development Organization
ResSim	Reservoir System Simulation	U.S. Army Corps of Engineers (USACE) Hydrologic Engineering Center (HEC) http://www.hec.usace.army.mil/
MODSIM	River Basin Management Decision Support System	Colorado State University (CSU) and U.S. Bureau of Reclamation (USBR) http://modsim.engr.colostate.edu/
WRAP	Water Rights Analysis Package	Texas Water Resources Institute (TWRI) and Texas Commission on Environmental Quality http://ceprofs.tamu.edu/rwurbs/wrap.htm
RiverWare	River and Reservoir Operations	University of Colorado CADSWES and USBR http://riverware.org/

Table 1. Selected representative generalized modeling systems

2. General characteristics of modeling systems

The generalized river/reservoir system management models explored in this chapter are based on volume-balance accounting procedures for tracking the movement of water through a system of reservoirs and river reaches. The model computes 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 rates.

From the perspective of the water management modeling systems addressed in this chapter, the spatial configuration of a river/reservoir system is represented by a set of model control points 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 stream flows are allocated between water users based on rules specified in the model. The models described in this chapter 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 multiple-purpose reservoir system operating rules and institutional water allocation mechanisms.

The models of this chapter 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.

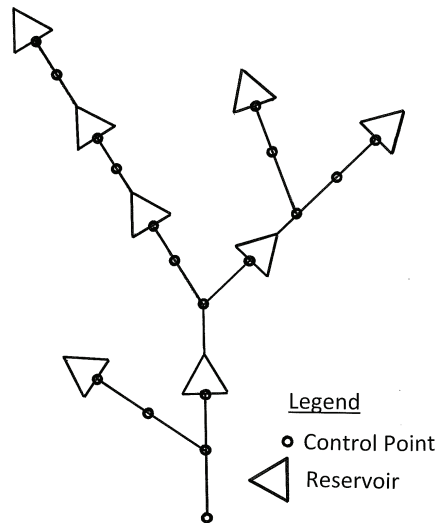


Fig. 1. Illustrative schematic of a river system as viewed from a modeling perspective

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 many-year hydrologic period-of-analysis reflecting a full range of fluctuating wet and dry periods including extended multiple-year drought.

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 stream flow and reservoir storage frequency analysis and supply reliability analysis capabilities are typically included in the modeling systems addressed by this chapter. Reservoir storage and stream flow 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 functions 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 issues may be pertinent to reservoir operations, separate models of river hydraulics are 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 chapter, 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 chapter 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 or 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 right 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.

3. Models for analyzing development and operation of reservoir systems

Pioneering efforts in computer simulation of reservoir systems include U.S. Army Corps of Engineers studies of six reservoirs on the Missouri River initiated in 1953, International Boundary and Water Commission simulations of the Rio Grande in 1954, and a simulation study of the Nile River Basin in 1955 (Maass et al., 1966). 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.

3.1 Optimization and simulation

Reservoir system analysis models have traditionally been categorized as simulation, optimization, and hybrid combinations of both. Development and application of decision-support tools within the 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.

The term *optimization* is used synonymously with *mathematical programming* to refer to a mathematical algorithm that computes a set of decision variable values which minimize or

maximize an objective function subject to constraints. Optimization is covered by water resources systems books (Karamouz et al., 2003; Jain & Singh, 2003; Simonovic, 2009) as well as numerous operations research and mathematics books. Thousands of journal and conference papers have been published since the 1960's 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 stream flows and other variables in the optimization models have been proposed (Labadie2004).

This chapter 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. Although optimization and simulation are two alternative modeling approaches with different characteristics, the distinction is obscured by the fact that models often contain elements of both. An optimization procedure may involve automated iterative executions of a simulation model. Optimization algorithms may be embedded within simulation models either to perform certain periphery computations or to provide the fundamental computational framework for the simulation model.

3.2 Network flow linear programming

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

$$\text{Minimize or Maximize } Z = \sum_{j=1}^n c_j x_j \quad (1)$$

$$\text{subject to } \sum a_{ij} x_j \leq b_i \text{ for } i = 1, \dots, m \text{ and } j = 1, \dots, n \quad (2)$$

$$x_j \geq 0 \text{ for } j = 1, \dots, n \quad (3)$$

A LP 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 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 chapter are based on network flow programming, which is a computationally efficient form of LP. 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.

$$\text{Minimize or Maximize } \sum \sum c_{ij} q_{ij} \text{ for all arcs} \quad (4)$$

$$\text{subject to } \sum q_{ij} - \sum q_{ji} = 0 \text{ for all nodes} \quad (5)$$

$$l_{ij} \leq q_{ij} \leq u_{ij} \text{ for all arcs} \quad (6)$$

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}
 u_{ij} is an upper bound on q_{ij}

The system is represented as a collection of nodes and arcs. 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 which 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 three parameters: a weighting, penalty, or unit cost factor c_{ij} associated with q_{ij} ; 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 LP 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.

3.3 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 reasons that water management practitioners were reluctant to apply mathematical optimization algorithms proposed by researchers that included deficiencies in databases, modeling inadequacies, institutional resistance to change, and the fundamental insensitivity of many actual systems to wide variations in design choices. Iich (2009) explores limitations of network flow programming. McMahon (2009) highlights the various complexities of applying computer models and concludes 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.

4. Generalized user-oriented 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 chapter. 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 U.S. Army Corps of Engineers (USACE) Institute for Water Resources, Wurbs (1994, 1995) inventoried generalized water management models in the categories of demand forecasting, water distribution systems, ground-water, watershed runoff, stream hydraulics, river and reservoir water quality, and reservoir/river system operations. Wurbs (2005a) later reviewed generalized reservoir/river system operations models in greater detail for the USACE. 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 U.S., the Hydrologic Modeling System (HMS) and River Analysis System (RAS) are probably applied most extensively. These and other models developed by the Hydrologic Engineering Center (HEC) of the USACE are available at the website shown in Table 1. HEC-HMS watershed precipitation-runoff and HEC-RAS river hydraulics modeling systems are combined with HEC-ResSim in the integrated Corps Water Management System for modeling reservoir system operations 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 multiple-purpose 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 (HMI) is maintained at Texas A&M University at the web site <http://hydrologicmodels.tamu.edu/> in collaboration with the U.S. Bureau of Reclamation. The HMI is updated periodically, including an update during 2010. Models are organized in various categories with summary descriptions provided for each model. The HMI includes the MIKE BASIN, CALSIM, MODSIM, RiverWare, and WRAP models cited later in this chapter. In addition to developing and maintaining the HMI, Singh and Frevert (2006) edited a book inventorying models focused primarily on watershed hydrology but also including 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 that have been 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).

This presentation focuses on modeling systems developed in the United States largely because the author's professional experience has been limited primarily to the United States. The U. S. is somewhat unique compared to most other countries in that generalized models are available in the public domain free-of-charge. Most, though not all, water management

software products developed with government funding in the U. S. are made accessible to the professional water management community without charging a fee for the software.

4.1 Models developed by international research and consulting organizations

However, reservoir/river system models are developed throughout the world. Three examples of the many non-U.S.-based modeling systems are cited as follows. The proprietary MIKE BASIN, WEAP, and OASIS software products were developed and are marketed by organizations that provide consulting services in applying the models. The developers and others have applied the models to reservoir/river systems throughout the world.

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 DHI family of software, integrates geographic information system capabilities with modeling river basin management. MIKE BASIN simulates multiple-purpose, multiple-reservoir 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 (WEAP) 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 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 Water Resources Engineering Simulation Language (WRESL) in the WRIMS-CALSIM model discussed next.

4.2 Models developed by state water agencies in the United States

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 U.S. Bureau of Reclamation developed the WRIMS and CALSIM modeling system (Draper et al., 2004) to replace an earlier California Department of Water Resources model.

The generalized WRIMS and California 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 (LP) solver, and graphics capabilities. The monthly time step simulation model is based on a LP formulation that minimizes a priority-based penalty function of delivery and storage targets. The LP model is solved for each month. Adjustment computations are performed after the LP solution 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. The user-supplied statements written in the WRESL language are used by the model to define the LP formulation. Time series data are stored, manipulated, and plotted using the Hydrologic Engineering Center (1995, 2009) Data Storage System (HEC-DSS), which is also used with WRAP, discussed later, as well as with HEC-ResSim and other HEC simulation models.

The Texas Water Development Board (TWDB) Surface Water Resources Allocation Model and Multiple-Reservoir Simulation and Optimization Model simulate and optimize the operation of an interconnected system of reservoirs, hydroelectric power plants, pump canals, pipelines, and river reaches using a monthly computational time step. The daily time step MONITOR also simulates complex surface water storage and conveyance systems operated for hydroelectric power, water supply, and low flow augmentation (Martin, 1983, 1987). The TWDB has adopted the WRAP modeling system, described later, for statewide and regional planning studies conducted in recent years, replacing these early TWDB models.

The early TWDB models, original California Department of Water Resources model, and the original versions of HEC-PRM and MODSIM discussed later are all based on the same network flow programming solution algorithm. An early version of WRAP was also developed using the same algorithm, but another simulation approach was actually adopted for WRAP. The original solution algorithms in HEC-PRM and MODSIM were later replaced with much more computationally efficient network flow programming algorithms.

4.3 Models developed by federal agencies in the United States

Most of the large federal reservoirs in the U.S. were constructed and are operated by the U.S. Army Corps of Engineers (USACE) or U.S. Bureau of Reclamation (USBR). The USACE has over 500 reservoirs in operation across the nation as well as many navigation locks, hydropower plants, and flood control structures. The USACE operates essentially all of the reservoir projects that it has constructed. The USBR has transferred operation of many of its projects to non-federal sponsors upon completion of construction but continues to operate about 130 reservoirs and appurtenant structures in the 17 western states. The USACE plays a dominant role in the U.S. in operating large reservoir systems for navigation and flood control. The USBR water resources development program was originally founded upon constructing irrigation projects to support development of the western U.S. The responsibilities of the two agencies evolved over time to emphasize comprehensive multiple-purpose water resources management.

The USACE and USBR developed many models for specific reservoir systems during the 1950's-1970's (Wurbs, 1996, 2005a). Many of these system-specific models have since been replaced with generalized models. The USBR currently uses RiverWare and MODSIM, which are described later in this chapter, and several remaining system-specific models. The USACE Hydrologic Engineering Center (HEC) maintains a suite of generalized simulation models that are widely applied by water agencies, consulting firms, and universities throughout the U.S. and the world. This chapter later focuses on HEC-ResSim but several other HEC products are also noted below.

The Corps Water Management System (CWMS) is the automated information system used by the USACE nationwide to support real-time operations of flood control, navigation, and multiple-purpose reservoir systems (Fritz et al., 2002). The CWMS is an integrated system of hardware and software that compiles and processes hydrometeorology, watershed, and project status data in real-time. A map-based user-friendly interface facilitates modeling and evaluation of river/reservoir system operations. CorpsView, a spatial visualization tool developed by the HEC based on commercially available geographic information system (GIS) software, provides a direct interface to GIS products and associated attribute information. The CWMS combines data acquisition/management tools with simulation models which include HEC-HMS (Hydrologic Modeling System), HEC-ResSim (Reservoir Simulation), HEC-RAS (River Analysis System), and HEC-FIA (Flood Impact Analysis).

The HEC-5 Simulation of Flood Control and Conservation Systems model (Hydrologic Engineering Center 1998) has been used since the 1970's in many USACE and non-USACE studies, including 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. However, HEC-5 is still available at the HEC website and continues to be applied by various model-users.

HEC-5 simulates multiple-purpose reservoir system operations for inputted unregulated stream flows and reservoir evaporation rates using a variable time interval. A monthly or weekly 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 stream flows 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 Prescriptive Reservoir Model (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. 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 also include non-economic components in the objective function. HEC-PRM applications to date have used a monthly time interval.

5. Selected state-of-the-art generalized modeling systems

The four user-oriented generalized models in Table 1 provide comprehensive capabilities for a broad spectrum of river/reservoir system modeling applications. ResSim, MODSIM, WRAP, and RiverWare are distinctly different from each other. However, as a group, the four alternative modeling systems are representative of the current state-of-the-art of professional practice in the United States in analyzing complex problems and issues in managing rivers and reservoir systems.

The four modeling systems were developed by water agencies and university research entities and have been extensively applied in both the U.S. and other countries. The software was developed for application by model-users other than the original developers and is accessible by water management professionals throughout the world. The 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 four 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 four alternative modeling systems and their predecessors have evolved through many versions over more than twenty 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 in the past and continue to be improved and expanded.

5.1 Hydrologic Engineering Center (HEC) Reservoir Simulation (ResSim) model

The USACE HEC initiated development of ResSim in 1996. ResSim was first released to the public in 2003 with the intention of eventually replacing HEC-5, which has been extensively applied for over 30 years. Documentation currently consists of a Users Manual (Hydrologic Engineering Center 2007) and other information found at the website in Table 1. ResSim is designed for application either independently of the previously discussed Corps Water Management System or as a component thereof. Applications have included the Sacramento and San Joaquin River Basins in California and Tigris and Euphrates River Basins in Iraq.

ResSim is comprised of a graphical user interface, computational program to simulate reservoir operation, data management capabilities, and graphics and reporting features. Multiple-purpose, multiple-reservoir systems are simulated using algorithms developed specifically for the model rather than formal mathematical programming methods. Meeting the needs of USACE reservoir control personnel for real-time decision support has been a governing objective in developing ResSim. The model is also applicable in planning studies. The full spectrum of multiple-purpose reservoir system operations is modeled. Particularly detailed capabilities are provided for modeling flood control operations.

The user-selected computational time-step may vary from 15 minutes to one day. Stream flow routing options include Muskingum, Muskingum-Cunge, modified Puls, and other methods. Stream flow hydrographs provided as input to ResSim can come from any source, including being generated with the HEC-HMS Hydrologic Modeling System. Multiple-reservoir systems, with each reservoir having multiple outlet structures, are modeled. Release decisions are based on specified storage zones that divide the pool by elevation and a set of rules that specify the goals and constraints governing releases when the storage level falls within each zone.

5.2 MODSIM river basin management decision support system

MODSIM is a general-purpose reservoir/river system simulation model based on network flow programming developed at Colorado State University (Labadie 2006; Labadie & Larson 2007). The model has evolved through many versions, with initial development dating back

to the 1970's. The USBR has been a primary sponsor of continued model improvements at Colorado State University. MODSIM has been applied in studies of a number of river systems in the western U. S. and throughout the world by university researchers in collaboration with various local, regional, and international water management agencies. 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 1) 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. The network flow programming problem is solved for each individual time interval. Thus, decisions are not affected by 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 and ground water.

5.3 Water rights analysis package (WRAP) modeling system

Development of WRAP at Texas A&M University began in the late 1980's sponsored by a cooperative research program of the U.S. Department of the Interior and Texas Water Resources Institute (TWRI). WRAP has been greatly expanded since 1997 under the auspices of the Texas Commission on Environmental Quality (TCEQ) in conjunction with implementing a statewide Water Availability Modeling (WAM) System (Wurbs, 2005b). The Texas Water Development Board, USACE, and other agencies have also sponsored improvements to WRAP. The software and documentation (Wurbs 2009, 2010, 2011a, 2011b; 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, publicly available TCEQ WAM System datasets are 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 WAM System consists of the generalized WRAP along with input datasets for the 23 river basins of Texas that include naturalized stream flows at about 500 gauged sites, watershed parameters for distributing these flows to over 12,000 ungauged locations, 3,450 reservoirs, water use requirements associated with about 8,000 water right permits reflecting two different water right systems, two international treaties, and five interstate compacts. WRAP is applied routinely with the WAM System input datasets for the individual river basins by water management agencies

and consulting engineering firms in regional and statewide planning studies, administration of the water right permit system, and other water management activities.

WRAP simulates water resources development, management, regulation, and use in a river basin or multiple-basin 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. Stream flow and reservoir storage is 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 for plotting and other analyses (Hydrologic Engineering Center, 1995, 2009).

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 monthly 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. Recently developed additional WRAP modeling capabilities include: short-term conditional reliability modeling; daily time step modeling capabilities that include flow forecasting and routing and disaggregation of monthly flows to daily; simulation of flood control reservoir system operations; and salinity simulation.

5.4 RiverWare reservoir and river operation modeling system

The U.S. Bureau of Reclamation (USBR) and Tennessee Valley Authority (TVA) jointly sponsored development of RiverWare at the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) of the University of Colorado (Zagona et al., 2001; Zagona et al., 2006). RiverWare development efforts date back to the mid-1990's, building on earlier software developed at CADSWES that extends back to the mid-1980's.

RiverWare provides the model-user with a software tools for constructing a model for a particular river/reservoir system and then running the model that 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 routs 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 three 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 LP solutions (Eschenbach et al., 2001). As additional goals are considered, the optimal solution of a higher priority goal is not sacrificed in order to optimize a lower priority goal.

The TVA applies RiverWare in optimizing the daily and hourly operation of the TVA system of multiple-purpose reservoirs and hydroelectric power plants. The USBR 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 USBR has also applied the model in the Rio Grande, Yakima, and Truckee River Basins. The USACE has recently sponsored addition of features to RiverWare for simulating flood control reservoir operations. Other entities have also applied the model in various river basins for various purposes.

6. Comparative summary of modeling capabilities

ResSim, MODSIM, WRAP, RiverWare, and other similar models provide flexible capabilities for analyzing multiple-purpose river/reservoir system operations. The models are water accounting systems that compute reservoir storages and releases and stream flows 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, ResSim, MODSIM, WRAP, and RiverWare 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.

6.1 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. Conservation operations are sometimes modeled with a daily interval, but monthly or weekly time steps are more common.

All four 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 three models was motivated primarily by conservation purposes, ResSim is flood control oriented. 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 LP option may optionally be economic costs or benefits. MODSIM and WRAP simulate salinity. RiverWare options include various water quality constituents. Groundwater sources and channel losses are included in the models. Surface/ground water interactions have been approximated in various ways. MODSIM has a groundwater routine, and has been linked with the U.S. Geological Survey MODFLOW groundwater model.

System analysis models are often categorized as being prescriptive or descriptive. With the exception of the optimization option in RiverWare, the four models are essentially descriptive simulation models that demonstrate what will happen if a specified plan is adopted. Prescriptive optimization models automatically determine the plan that will best satisfy the decision criteria. 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.

6.2 Computational structure

The term *ad hoc* in Table 2 refers to computational strategies developed specifically for a particular model, as contrasted with linear programming (LP) which is a generic algorithm incorporated in numerous models. ResSim and WRAP are organized based upon ad hoc model-specific computational frameworks. MODSIM is based on network flow LP. RiverWare has two alternative solution options based on ad hoc algorithms and a third option that uses LP. The LP-based models have additional ad hoc algorithms used along with their LP solver, but the LP 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 LP models, the entire LP solution of the whole system is repeated iteratively. With the ad hoc simulation procedures, the computations for an individual reservoir are repeated iteratively.

Modeling System	Programming Language	Computational Approach	Computational Time Step
ResSim	Java	ad hoc	15 minutes to day
MODSIM	C++, .NET, Basic.NET	network LP	month, week, day
WRAP	Fortran	ad hoc	month, day, other
RiverWare	C++	ad hoc and LP	hour to year

Table 2. Alternative development frameworks

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 LP and goal programming. Computations are performed simultaneously for all the time intervals. Thus, model results show a set of reservoir storages and releases which minimize or maximize a defined objective function assuming all future stream flows are known as release decisions are made simultaneously during each period. With the exception of options for short-term flow forecasting, 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.

Many other prescriptively oriented optimization models reported in the research literature, including the HEC-PRM Prescriptive Reservoir Model described earlier in this chapter, adopt the approach of optimizing an objective function while simultaneously considering all time steps of the entire hydrologic period-of-analysis. Thus, these models reflect perfect knowledge of future hydrology. 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. Descriptive simulation models are more realistic in that current operating decisions in the model are not affected by future hydrology and future operating decisions.

6.3 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 four modeling systems has its own unique framework within which the user constructs and implements a model for a particular reservoir/river system. With 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 programs, 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 three optional solution options.

The user interfaces of the models reflect both similarities and significant differences. 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 and 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 ResSim connect with and rely upon graphics capabilities of the Hydrologic Engineering Center (HEC) Data Storage System (DSS). Geographic information system (GIS) tools are included in all four of the modeling systems.

The compiled executable software products were developed in the programming languages shown in Table 2. 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 absolutely error-free software may be an idealistic goal yet to be achieved. Dealing with errors introduced by users in model input data is important. The modeling systems contain various mechanisms for detecting and correcting blunders and inconsistencies in input data.

The organizations and individuals that originally developed the four modeling systems continue to improve the models and support their application. 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. The HEC periodically provides training courses in the application of HEC-ResSim. The TWRI periodically provides training courses in the application of WRAP.

RiverWare is designed for Unix workstations but is also used on personal computers with Microsoft Windows. The other three modeling systems are usually executed on personal computers with Microsoft Windows but can also be applied with other computer systems.

7. Conclusions

The evolution of computer modeling of systems of rivers and reservoirs that began in the 1950's 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. ResSim, MODSIM, WRAP, RiverWare, and other similar models, though continuing to be improved and expanded, are well established and significantly contributing to water management in the United States and throughout the world. These generalized modeling systems are readily available for application by water management professionals to river systems located anywhere in the world.

Generalized modeling systems reflect the types of applications that motivated their development. ResSim serves as the reservoir system operations component of the Corps Water Management System implemented in the USACE district offices nationwide to support real-time operations of multiple-purposes reservoirs and flood control and navigation projects. ResSim is also used in USACE planning studies. RiverWare was developed as a partnership between CADSWES and the USBR and TVA. The TVA uses ResSim to support real-time hydroelectric power system operations within the setting of multiple-purpose reservoir system operations. The USBR applies RiverWare for both long-term planning and short-term operational planning for its multiple-purpose reservoir systems. The network flow programming based MODSIM was developed at Colorado State University in collaboration with the USBR and has been applied primarily by university researchers in studies both in the United States and abroad. WRAP supports statewide and regional planning and water allocation regulatory activities in Texas that require detailed modeling of diverse and complex institutional water allocation arrangements and reservoir/river system management practices.

ResSim, RiverWare, MODSIM, and WRAP provide general frameworks for constructing and applying models for specific systems of reservoirs and river reaches. Each of these four

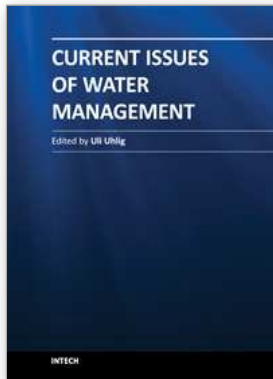
generalized modeling systems is based upon its own set of data management and computational techniques and has its own terminology, but they all provide flexible broad-based generic capabilities for modeling and analysis of river system development and management.

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There is an estimated 1.4 billion km³ of water in the world but only approximately three percent (39 million km³) of it is available as fresh water. Moreover, most of this fresh water is found as ice in the arctic regions, deep groundwater or atmospheric water. Since water is the source of life and essential for all life on the planet, the use of this resource is a highly important issue. "Water management" is the general term used to describe all the activities that manage the optimum use of the world's water resources. However, only a few percent of the fresh water available can be subjected to water management. It is still an enormous amount, but what's unique about water is that unlike other resources, it is irreplaceable. This book provides a general overview of various topics within water management from all over the world. The topics range from politics, current models for water resource management of rivers and reservoirs to issues related to agriculture. Water quality problems, the development of water demand and water pricing are also addressed. The collection of contributions from outstanding scientists and experts provides detailed information about different topics and gives a general overview of the current issues in water management. The book covers a wide range of current issues, reflecting on current problems and demonstrating the complexity of water management.

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