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Reservoir/River System Analysis Models: Conventional Simulation versus Network Flow Programming

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ABSTRACT *Conventional simulation models and network flow programming are two widely used alternative approaches for analysing reservoir/river systems. Conventional simulation models typically provide greater flexibility in representing the complexities of real-world systems. Network flow programming provides capabilities to search systematically and efficiently through numerous possible combinations of decision variable values, with a more prescriptive modelling orientation. A comparative evaluation of the alternative modelling approaches is presented. The Water Rights Analysis Program (TAMUWRAP) provides a case study for the comparative evaluation. For this particular application, neither modelling approach was found to have a clearly defined advantage over the other. However, in general, the characteristics of the alternative modelling approaches result in each being most appropriate in certain situations. The different models can also be used in combination.*

Introduction

Development and operation of reservoir/river systems is an important and complex area of water resources planning and management. A broad array of computer models and analysis techniques are available for evaluating river basin systems and supporting various decision-making processes. These models have traditionally been categorized as (1) simulation, (2) optimization, and (3) combinations of simulation and optimization. A simulation model is a representation of a system used to predict the behaviour of the system under a given set of conditions. Alternative executions of a simulation model are made to analyse the performance of the system under varying conditions, such as for alternative operating policies. Optimization (mathematical programming) models are based on a formulation in which a formal algorithm is used to compute a set of decision variable values which minimize or maximize an objective function subject to constraints. Reservoir/river system analysis models have been developed based on linear programming, dynamic programming and various other nonlinear programming techniques.

Although optimization and simulation are two alternative modelling approaches with different characteristics, the distinction is somewhat obscured by the fact that many models, to various degrees, contain elements of both approaches. All 'optimization' models also 'simulate' the system. Optimization algorithms are embedded within many simulation models to perform certain computations. The term 'conventional' is used here to refer to simulation models which do not contain a formal mathematical programming algorithm. Conventional simulation models consist of collections of computational algorithms developed for the particular model to perform various tasks.

Comprehensive state-of-the-art reviews of reservoir/river system modelling capabilities are provided by Yeh (1985) and Wurbs (1991, 1993). The present paper focuses on comparing two alternative types or categories of models: (1) conventional simulation models and (2) network flow programming models. Development and application of decision-support tools within the major water resources development agencies in the United States have focused on conventional simulation models. The academic community and research literature have emphasized optimization techniques. Network flow programming models are particularly notable from the perspective of combining advantageous features of simulation with a formal optimization algorithm. Both categories of models have proven records of practical application, as compared with many other more mathematically sophisticated models which have been addressed extensively in academic research. Generalized models from both categories are readily available for application by water managers.

The paper is written from the perspective of water managers and/or model developers faced with the question of selecting a modelling approach for a particular application. The paper is based on a review of the literature supplemented with a case study analysis. The case study consisted of developing and applying two versions of a particular reservoir/river system analysis model, with and without use of network flow programming.

Conventional Simulation Models

Simulation modelling of major river basins in the United States began in 1953 with a study by the US Army Corps of Engineers (USACE) of the operation of six reservoirs on the Missouri River. The objective was to maximize hydroelectric power generation subject to constraints imposed by specified requirements for navigation, flood control and irrigation. Coincidentally, the USACE recently modelled the Missouri River System using the Hydrologic Engineering Center Prescriptive Reservoir Model (HEC-PRM) network flow programming model discussed in the next section. Early simulation models as well as many of the more recently developed models are for specific river/reservoir systems. Notable examples include the Potomac River Interactive Simulation Model and the Colorado River Simulation System (Wurbs, 1991). A recent inventory of models prepared by the US Bureau of Reclamation (1991) includes a number of such project-specific models.

The term 'generalized' is used here to refer to computer programs designed for a range of modelling applications involving essentially any reservoir/stream system. The user develops the input data for the particular system of interest, in a specified format, and executes the model without being concerned with developing or modifying the actual computer code. A number of generalized models are readily available.

The USACE Hydrologic Engineering Center (HEC) has developed a series of generalized water-related simulation models used extensively throughout the United States and internationally as well. HEC models include HEC-3 Reservoir System Analysis and HEC-5 Simulation of Flood Control and Conservation

Systems. Various publications available from the HEC on use of these models include users manuals, training documents, and reports on specific applications. The USACE North Pacific Division developed the Streamflow Synthesis and Reservoir Regulation (SSARR) and Hydropower System Regulation Analysis (HYSYS) models, which are also widely used (Wurbs, 1991).

The Reservoir Operating Quality Routing Program (RESOP-II) computes the firm yield of a single reservoir. A quality routeing option adds the capability to route up to three non-degradable constituents through the reservoir (Browder, 1978). The Massachusetts Institute of Technology MITSIM Model (Strzepek *et al.*, 1989) provides capabilities for evaluating the economic as well as hydrologic performance of a river basin system involving hydroelectric power, irrigation, and municipal and industrial water supply. The distinctive feature of the Interactive River System Simulation Program (IRIS) is its extensive use of interactive computer graphics for information transfer between machine and user (Loucks *et al.*, 1989). The interactive graphics orientated River System Simulation System (RSS) is being developed at the Center for Advanced Decision Support for Water and Environmental Systems at the University of Colorado, sponsored by the Bureau of Reclamation.

Network Flow Programming Models

The simulation models cited above are 'conventional' simulation models in the sense that no formal mathematical programming algorithms are used. Many network flow models can also be categorized as being descriptive simulation models in the sense that they are applied in the same manner as conventional simulation models. However, network flow programming also allows development of models with a more prescriptive orientation.

Network flow programming is a computationally efficient form of linear programming which is used in a broad range of systems engineering and operations research applications (Jensen & Barnes, 1980). Most reservoir/river system analysis applications of network flow programming are formulated as a minimum cost capacitated network flow problem, which has the following general format.

$$\text{minimize} \quad \sum_{i=1}^{n} \sum_{j=1}^{n} C_{ij} q_{ij} \qquad (1)$$

$$\text{subject to} \quad \sum q_{ij} - \sum q_{ij} = 0 \qquad \text{for each node} \qquad (2)$$

$$\text{and} \quad l_{ij} \leq q_{ij} \leq u_{ij} \qquad \text{for each arc} \qquad (3)$$

The network flow programming algorithm computes the flows (q_{ij}) in each of n arcs (node i to node j) which minimizes a weighted objective function, subject to constraints which include maintaining a mass balance at each node and not violating user-specified upper and lower bounds on the flows. Each arc has three parameters: (1) a weighing, penalty or unit cost factor (c_{ij}) associated with q_{ij}, (2) lower bound (l_{ij}) on q_{ij} and (3) upper bound (u_{ij}) on q_{ij}. Flows (q_{ij}) represent streamflows, diversions and storage changes. Nodes are connected by arcs representing the way 'flow' can be conveyed. The weighing factor (c_{ij}) could be a unit cost in dollars or, alternatively, a penalty or utility term which provides a mechanism for expressing relative priorities for use in defining operating rules.

Generalized reservoir system analysis models can be designed so that the user simply provides the required input data, with the network flow formulation being essentially transparent. Efficient network solvers, such as the out-of-kilter algorithm, are available for performing the computations. Network flow programming provides considerable flexibility for formulating a particular river basin modelling application. An optimization problem, as formulated above, can be solved for each individual time interval in turn, or, alternatively, a single network flow problem can be solved for all time intervals of the overall period of analysis simultaneously. Convex piecewise linear penalty functions can be represented with a q_{ij}, c_{ij}, l_{ij} and u_{ij} for each linear segment. Successive iterative algorithms are used to handle nonlinearities such as those associated with evaporation and hydroelectric power computations. A number of reservoir system analysis models which incorporate network flow programming have been reported in the literature. Several such models considered to be representative of the state of the art are cited below.

A network flow programming model of a complex multiple-reservoir multiple-purpose system in the Trent River Basin in Ontario, Canada has been applied in both planning studies and real-time operations (Sigvaldason, 1976; Bridgeman *et al.*, 1988). A time-based rule curve and storage zone representation of reservoir operating rules in the model is similar to the previously cited HEC-5. The optimization submodel for making release decisions during each time interval is similar to the approach used in the Texas Water Development Board models, discussed below, except for differences in the objective functions.

The Texas Water Development Board has developed several generalized simulation models based on network flow programming. SIMYLD-II simulates storage and transfer of water within a system of reservoirs, rivers and conduits on a monthly basis with the objective of meeting a set of specified demands in a given order of priority. The Surface Water Allocation Model (AL-V) and Multireservoir Simulation and Optimization Model (SIM-V) simulate and optimize the operation of an interconnected system of reservoirs, hydroelectric power plants, pump canals, pipelines and river reaches (Martin, 1983). SIM-V is used to analyse short-term reservoir operations. AL-V is for long-term operations. Hydroelectric benefits, which are complicated by nonlinearity, are incorporated by solving successive network flow problems.

Beard *et al.* (1972) compared the previously cited HEC-3 and SIMYLD by analysing a case study system using each model alternatively. They concluded that both models appeared to simulate the operation of a complex water resource system as accurately as pertinent functions and features of the system can be described. Both models yield similar results. SIMYLD had the flexibility not available in HEC-3 of simulating a closed loop. The computational speed of SIMYLD was found to be about twice as fast as HEC-3.

The various versions of MODSIM were developed at Colorado State University, based originally on modifying the Texas Water Development Board SIMYLD-II model (Labadie *et al.*, 1984). MODSIM is a generalized river basin network simulation model which allocates water based on user-specified priorities. The Central Resource Allocation Model (CRAM) was developed for use in preparing a water supply master plan for the city of Boulder, Colorado (Brendecke *et al.*, 1989). Development of CRAM built upon MODSIM with various improvements pertinent to the particular application being added. The Water Assignment Simulation Package (WASP) was developed to analyse the water supply system of the city of Melbourne, Australia but is generalized for application to other water supply systems as well (Kuczera & Diment, 1988).

The DWRSIM model, developed by the California Department of Water Resources, simulates the operation of the Central Valley Project and State Water Project storage and conveyance systems. The original DWRSIM is a conventional simulation model developed based on modifying HEC-3. DWRSIM was subsequently revised to incorporate a network flow programming algorithm (Chung *et al.*, 1989). The versions of DWRSIM with and without the network flow algorithm are used for the same types of analyses. The input and output data formats are essentially the same. The network flow model was incorporated into DWRSIM to enhance capabilities for analysing consequences of different operational scenarios, with the improvements including capabilities to: (1) give different relative priorities to the different demand points and to the different components that make up a demand point, (2) allocate storage within a reservoir to specific demands, and (3) provide a better balance among the reservoirs in the system (Chung *et al.*, 1989).

The Hydrologic Engineering Center (HEC) Prescriptive Reservoir Model (PRM) was recently developed in conjunction with studies of reservoir systems in the Missouri and Columbia River Basins (Burnham & Davis, 1992). However, HEC-PRM is generalized for application to any reservoir system. Reservoir release decisions are made based on minimizing costs in connection with convex piecewise linear penalty functions associated with various purposes such as hydroelectric power, recreation, water supply, navigation and flood control.

TAMUWRAP Case Study

TAMUWRAP (Wurbs *et al.*, 1993) is a Water Rights Analysis Package (WRAP) developed at Texas A&M University (TAMU). The generalized computer model simulates management of the streamflow and reservoir storage resources of a river basin, under an appropriative water rights permit system where water is allocated among users based on assigned priorities. Studies involving application of the original version of TAMUWRAP, and also HEC-3 and HEC-5, to the Brazos River Basin have been reported previously (Wurbs & Walls, 1989; Wurbs & Carriere, 1993). The original model incorporates no mathematical programming algorithms. A recent research project involved development of a network flow programming version of the model and testing it with previously developed Brazos River Basin data sets (Yerramreddy, 1993). Thus, TAMUWRAP provides a case study for comparing network flow versus conventional simulation models for this particular type of application.

Description of TAMUWRAP

The TAMUWRAP package includes several computer programs, called WRAP2, WRAP3, WRAPNET, WRAPQ and TABLES. A river/reservoir system simulation may be performed with either of two alternative versions of the Water Rights Analysis Program (WRAP2 or WRAP3). The postprocessor program TABLES performs various manipulations of WRAP2 and WRAP3 input and output data to organize and present the simulation results in various optional formats. WRAP3 contains all the capabilities of WRAP2 plus additional optional features related primarily to multiple-reservoir operating policies and hydroelectric power. A water quality version of the simulation model (WRAPQ) was recently developed which incorporates salinity considerations (Wurbs *et al.*, 1993).

WRAPNET (Water Rights Analysis Program—Network Flow Programming Version) is equivalent to WRAP2. WRAPNET and WRAP2 read the same input file and create the same output file. Most of the optional WRAP3 and WRAPQ features could also be incorporated in WRAPNET, but significant time and effort would be required. The program TABLES is used in the same way with either WRAPNET, WRAP2, WRAP3 or WRAPQ to organize the simulation results.

TAMUWRAP is designed for use in various types of planning studies to evaluate alternative water management strategies for specified water use scenarios. Model results can be used to evaluate the capability of a river basin to meet specified current or future demands. Reservoir system simulation studies can be performed to evaluate alternative operating policies or the impacts of adding new reservoirs to a system. A simulation is typically based on maintaining specified water use requirements and operating policies during an assumed repetition of historical hydrology.

The WRAP model (any version) provides the capability to simulate a river/reservoir system involving essentially any tributary configuration. Inter-basin transfers of water can also be included in the simulation. The location of reservoirs, diversions and other system components are represented by a set of control points. Input data include:

- naturalized streamflows at each control point for each month of the simulation, which have been adjusted to reflect unregulated or pre-development conditions;
- control point location, diversion amount, storage capacity, priority date, type use and return flow specifications for each water right;
- storage versus area relationships for each reservoir;
- reservoir evaporation rates; and
- monthly water use distribution factors for each water use type.

Model output, for each month of the simulation, includes:

- unappropriated streamflows and streamflow depletions for each control point;
- storages, evaporation volumes, inflows and releases for each reservoir; and
- diversions and shortages for each diversion requirement.

The output data are extremely voluminous. TABLES allows the results to be presented in various formats and develops various summary statistics including volume and period reliabilities.

Comparison of Conventional Simulation versus Network Flow Programming

With either of the models, the computations are performed for each individual month in turn. WRAPNET performs the internal computations differently from WRAP2 and WRAP3. In a given month, WRAP2 or WRAP3 consider each water right in priority order, and repeat the streamflow and storage accounting computations for each individual right in turn. For each month, WRAPNET solves a network flow programming problem involving a large system of equations in the format of equations 1–3. The flows (q_{ij}) include instream flows, diversions and reservoir storage changes. The priority numbers for the water rights, representing appropriation dates, are reflected in the c_{ij} of equation 1. Since reservoir storage depends on evaporation, which is a function of storage, iterative computations are performed to handle the nonlinearity. WRAP2 and WRAP3 iteratively compute the storage, evaporation and other variables associated with one water right at a time in priority order. WRAPNET iteratively solves the entire network flow problem several times each month.

The alternative versions of the WRAP models were applied to a data set developed for the Brazos River Basin (Wurbs & Walls, 1989). The 118 000 km^2 Brazos River Basin extends from New Mexico across the state of Texas to the Gulf of Mexico. About 1040 individual citizens, private companies, cities and public agencies hold permits to use the waters of the Brazos River and its tributaries. The water rights include diversions totalling 84.9 m^3/s and storage capacities totalling 5635 million m^3 in 598 reservoirs. Municipal, industrial, irrigation and mining uses account for 51%, 29%, 19% and 1%, respectively, of the total permitted water use. The simulation uses a monthly time step and 1900–1984 simulation period. Naturalized streamflows are input for 1020 months at 19 locations. The WRAPNET internal network flow formulation includes 4221 arcs and 708 nodes. Thus, referring to equations 1–3, values for 4221 q_{ij} are computed by WRAPNET for each month.

A TAMUWRAP analysis of the Brazos River Basin had already been completed prior to development of WRAPNET. Development of WRAPNET and its application to the existing data sets was accomplished in order to compare the alternative modelling approaches (Yerramreddy, 1993). WRAPNET provides all the modelling capabilities of WRAP2. Although significant time and effort would be required, WRAPNET could be expanded to incorporate essentially all of the additional optional WRAP3 capabilities related to more complex multiple-reservoir operating policies and the inclusion of hydropower.

For this particular type of river/reservoir system modelling application, the same modelling capabilities can be provided equivalently with either the conventional simulation model or the network flow programming model. The alternative versions of WRAP are executed in the same way, with the same input data file, and provide the same results. No clearly defined advantage of one model over the other could be found.

WRAP2 and WRAP3 run much faster than WRAPNET. The Brazos River Basin simulation on an 80486/33 microcomputer requires about 15 minutes for WRAP3 compared with several hours for WRAPNET. However, the speed of WRAPNET could probably be increased with a more efficient network flow programming algorithm. For example, the original version of the HEC-PRM model, which was developed by the USACE Hydrologic Engineering Center (HEC) during 1990–92, used an out-of-kilter algorithm comparable to the network solver in WRAPNET. Run times were found to be excessive, and consequently a much more efficient linear programming algorithm was developed for the HEC-PRM during 1992.

The conclusion of the case study is that either the conventional simulation approach or the network flow programming approach could be used successfully with the TAMUWRAP model. The conventional simulation approach will actually be adopted in future work with TAMUWRAP. However, TAMUWRAP represents just one particular type of river/reservoir system modelling. The following comparative evaluation of the network flow versus conventional modelling approaches is from the broader perspective of river/reservoir system models in general.

Comparative Advantages and Disadvantages

Both conventional simulation models and network flow models are useful water resources planning and management tools. Neither approach is likely to replace the other. However, the alternative approaches have certain characteristics which should be considered in formulating a modelling approach for a particular application. Since conventional simulation models are not constrained to a particular mathematical format, they typically provide greater flexibility in representing the complexities of real-world systems. The advantages of network flow programming, and optimization techniques in general, are related to capabilities: (1) systematically and efficiently to search through large numbers of combinations of values of decision variables; and (2) to provide a more prescriptive orientation. Another closely related characteristic of mathematical programming is that problems can be formulated to solve all time periods simultaneously. Network flow programming also has the advantage of being a well-defined algorithm. The same network solver routine can be incorporated into different models representing a wide range of applications. These relative advantages and disadvantages are discussed below.

Representation of Real-world Complexities

In general, the complexities of real-world systems can be represented more realistically by conventional simulation models than by optimization models. The relatively rigid format of network flow and other mathematical programming formulations limit their applicability. However, various mechanisms are available for incorporating nonlinearities and other complexities in optimization models. Also, the network programming algorithm can be used to perform only a selected portion of the model computations. For example, the nonlinear reservoir evaporation and storage computations are handled in WRAPNET by iteratively executing the network solver. A number of additional computations are performed in WRAPNET each month after completion of the network flow solution. Simulation models based on network flow programming tend to provide greater flexibility than conventional simulation models for specifying relative priorities between competing uses and users. TAMUWRAP is an exception in this regard. Whereas the computations proceed from upstream to downstream in most conventional simulation models, the WRAP computations proceed in priority order. The WRAP model handles complex water use priorities and closed loops even without using network flow programming.

Reservoir purposes represent a key consideration in formulating a modelling approach. The distinction between flood control and conservation purposes, such as hydroelectric power, irrigation, and municipal and industrial water supply, is particularly significant. Flood control operations typically involve multiple-reservoir releases to multiple downstream control points with maximum allowable streamflow targets often being a function of storage. Flood wave attenuation effects are important. Estimating expected annual flood damages is often an important part of the study. These types of considerations are much more amenable to incorporation in a simulation model like HEC-5 rather than adhering to the relatively strict mathematical format requirements of optimization algorithms. Hydroelectric power computations are nonlinear but can be incorporated in a linear network flow programming model by successive iterations of the network solver.

Prescriptive versus Descriptive Orientation

System analysis models are often categorized as being either descriptive or prescriptive. Descriptive models demonstrate what will happen if a specified plan is adopted. Prescriptive models automatically determine the plan which should be adopted to best satisfy the decision criteria. Simulation models are generally descriptive. Optimization techniques greatly enhance capabilities to develop models which are more prescriptive.

Many, if not most, reservoir/river system analysis models based on network flow programming are description simulation models. The descriptive models do not automatically find an optimal set of reservoir release and storage values, but do show the releases and storages which would result from a particular operating plan. The descriptive models have the advantage of allowing the user to define more precisely the operating plan. Prescriptive models provide the advantage of determining the sequences of operating decisions which optimize a specified criterion function. The Hydrologic Engineering Center Prescriptive Reservoir Model (HEC-PRM) is an example of a prescriptive network flow model. HEC-PRM determines releases which minimize economic cost associated with convex penalty functions for the various project purposes such as hydroelectric power, navigation, municipal and industrial water supply, irrigation, recreation and flood control.

Economic evaluations can be incorporated in either conventional simulation models or network flow models. In either case, an economic objective function can be used as a measure of optimality. Whereas network flow programming automatically searches for an optimum decision policy, a conventional simulation model requires multiple runs to evaluate alternatives. Thus, network flow programming provides useful capabilities for analysing problems characterized by a need to consider a large number of combinations of values for the decision variables. However, the economic evaluation in a conventional simulation model is not constrained to the objective function format of equation 1. Thus, a broader range of economic evaluation methods can be used with conventional simulation models. When economic considerations are reflected in any system analysis model, the computer model simply computes dollars as a function of computed storages, diversions and instream flows. The difficult, time-consuming part of the study is developing a conceptual basis and supporting field data for assigning benefits and costs which can be incorporated in the model input data.

Most of the network flow models cited here and essentially all conventional simulation models step through time one period at a time. Computations in a given period are not affected by future periods. This is consistent with the real world, since future streamflows and other future conditions are unknown when release decisions are made. However, the more prescriptive optimization models are typically formulated to consider all time periods simultaneously. This option is not available with conventional simulation models.

The HEC Prescriptive Reservoir Model (HEC-PRM) performs the computations simultaneously for all the time intervals, as contrasted with SIMYLD-II, MODSIM, DWRSIM and WRAPNET, which allocate water and storage resources to competing demands based on user-specified priorities and operating rules for each time interval in turn, with the computations proceeding period by period. The HEC-PRM determines a set of reservoir releases which would minimize cost, as defined by user-input cost functions, for the given inflow sequences, assuming perfect knowledge of future flows each time a release decision is made. Thus, HEC-PRM shows the best possible value of the objective function, along with one set of corresponding values for all the releases and all other variables, which can be achieved with the given inflows. Since, in the real world, future streamflows are not actually known when a release decision is made, the model provides an upper limit or best possible scenario on what can be achieved. Although the model provides only one set of decision variable values, combinations of a range of values for each variable may result in the same value of the objective function.

Optimization and simulation models can be used in combination to realize the advantages of both the prescriptive and descriptive approaches. For example, HEC-PRM can be used to sort through the infinite combinations of release decisions to find a set of releases and corresponding storages which 'optimizes' economic efficiency. The HEC-PRM output data could then used, with judgement and some quantitative analysis, as a general guide to designing alternative operating rules. The alternative operating plans could then be evaluated in greater detail using one of the previously cited conventional simulation models or network flow models.

Summary and Conclusions

Both conventional simulation models and network flow models have been applied extensively in the evaluation of river/reservoir systems. Numerous reservoir/river system optimization models based on other linear and nonlinear programming techniques are also reported in the literature. The selection of a modelling and analysis approach for a particular application depends on the characteristics of the application, analysis capabilities provided by alternative models, and the background and preferences of the analysts. In some modelling situations, conventional simulation models and network flow programming models are essentially equivalent in their applicability. In other situations, a particular modelling approach may provide significant advantages. In some cases, the most effective modelling approach might involve the use of both types of models in combination. Conventional simulation modelling is not constrained to a specified mathematical format and thus generally, but not necessarily always, provides greater flexibility for representing the complexities of real-world systems. Network flow programming, as well as other optimization methods, is advantageous from the perspectives of: (1) providing capabilities to search systematically and efficiently through an infinite number of possible combinations of values for numerous decision variables; (2) providing a more prescriptive orientation; and (3) providing generic solution algorithms which can be applied in a broad range of diverse applications. Although network flow programming is a very computationally efficient form of linear programming, computer memory and execution times can still be a significant consideration.

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References

Beard, L.R., Weiss, A. & Austin, T.A. (1972) *Alternative Approaches to Water Resources System Simulation,* Technical Paper No. 32 (Davis, CA, USACE Hydrologic Engineering Center).

Brendecke, C.M., DeOreo, W.B., Payton, E.A. & Rozaklis, L.T. (1989) Network models of water rights and system operations, *Journal of Water Resources Planning and Management,* 115(5), pp. 684–696.

Bridgeman, S.G., Norrie, D.J.W., Cook, H.J. & Kitchen, B. (1988) Computerized decision-guidance system for management of the Trent River Multireservoir System, in: Labadie, Brazil, Corbu & Johnson (Eds) *Computerized Decision Support Systems for Water Managers,* (New York, American Society of Civil Engineers), pp. 582–592.

Browder, E. (1978) *RESOP-II Reservoir Operating and Quality Routing Program,* Program Documentation and User's Manual, UM-20 (Austin, TX, Texas Water Development Board).

Burnham, M.W. & Davis, D.W. (1992) HEC-PRM application: Missouri River Reservoir System, paper presented to the Fourth Water Resources Operations Management Workshop, American Society of Civil Engineers, York, NY.

Chung, F.I., Archer, M.C. & DeVries, J.J. (1989) Network flow algorithm applied to California Aqueduct simulation, *Journal of Water Resources Planning and Management,* 115(2), pp. 131–147.

Jensen, P.A. & Barnes, J.W. (1980) *Network Flow Programming,* (New York, Wiley).

Kuczera, G. & Diment, G. (1988) General Water Supply System Simulation Model: WASP, *Journal of Water Resources Planning and Management,* 114(4), pp. 365–382.

Labadie, J.W., Pineda, A.M. & Bode, D.A. (1984) *Network Analysis of Raw Supplies under Complex Water Rights and Exchanges: Documentation for Program MODSIM3,* (Fort Collins, CO, Colorado Water Resources Institute).

Loucks, D.P., Salewicz, K.A. & Taylor, M.R. (1989) *IRIS An Interactive River System Simulation Model, General Introduction and Description,* (Ithaca, NY, Cornell University, and Laxenburg, Austria, International Institute for Applied Systems Analysis).

Martin, Q.W. (1983) Optimal operation of multiple reservoir systems, *Journal of Water Resources Planning and Management,* 109(1), pp. 58–74.

Sigvaldason, O.T. (1976) A simulation model for operating a multipurpose multireservoir system, *Water Resources Research,* 12(2), pp. 263–278.

Strzepek, K., Garcia, L. & Over, T. (1989) *MITSIM 2.1 River Basin Simulation Model,* User Manual (Boulder, CO, Center for Advanced Decision Support for Water and Environmental Systems, University of Colorado).

US Bureau of Reclamation (1991) *Inventory of Hydrologic Models* (Denver, CO, US Bureau of Reclamation), 80 pp.

Wurbs, R.A. (1991) *Optimization of Multiple-Purpose Reservoir System Operations: A Review of Modeling and Analysis Approaches,* Research Document No. 34 (Davis, CA, US Army Corps of Engineers, Hydrologic Engineering Center), 88 pp.

Wurbs, R.A. (1993) Reservoir system simulation and optimization models, *Journal of Water Resources and Planning and Management,* 119(4), pp. 455–472.

Wurbs, R.A. & Carriere, P.E. (1993) Hydrologic simulation of reservoir storage reallocations, *International Journal of Water Resources Development,* 9(1), pp. 51–64.

Wurbs, R.A., Dunn, D.D. & Walls, W.B. (1993) *Water Rights Analysis Package (TAMUWRAP),* Model Description and Users Manual, Technical Report 146, (College Station, TX, Texas Water Resources Institute). 182 pp.

Wurbs, R.A. & Walls, W.B. (1989) Modeling and analysis of water rights, *Journal of Water Resources Planning and Management,* 115(4), pp. 416–430.

Yeh, W.W.-G. (1985) Reservoir management and operations models: a state-of-the-art review, *Water Resources Research*, 21(12), pp. 1797–1818.

Yerramreddy, A. (1993) Comparative evaluation of network flow programming and conventional reservoir system simulation models, MSc thesis, Texas A&M University, College Station, Texas, 128 pp.