MODSIM: Decision Support System for Integrated River Basin Management

John W. Labadie
MODSIM: Decision Support System for Integrated River Basin Management

John W. Labadie
Department of Civil Engineering, Colorado State University, Fort Collins, CO 80523-1372, USA

Abstract: MODSIM 8.0 is a generic river basin management decision support system for analysis of long term planning, medium term management, and short term operations on desktop computers operating under MS Windows 2000/XP. MODSIM is free from expensive licenses for proprietary software since all components are developed from native code or shareware under the MS .NET Framework. MODSIM includes a powerful, interactive graphical user interface for creating, locating and connecting river basin network components, as well as spreadsheet-style data editing in an object-oriented spatial data base management system. Flexible data import and export tools are included for interaction with external data base management systems. One of the greatest advantages of the MS .NET Framework is the ability to customize MODSIM for any specialized operating rules, input data, output reports, and access to external modules such as water quality models running concurrently with MODSIM, all without having to modify the original source code. The basic solver in MODSIM is a state-of-the-art network flow optimization algorithm up to two orders of magnitude faster than solvers in other river basin modeling packages and capable of simulating complex, large-scale networks. An iterative solution procedure allows consideration of non-network and conditional constraints. GEO-MODSIM, a full implementation of MODSIM operating as a custom extension in ArcGIS (ESRI, Inc.), allows automatic generation of MODSIM networks from geometric networks and processing of spatial database information in a GIS.

Keywords: River basin management; Decision support systems; Network flow simulation; Geographic information systems

1. INTRODUCTION

Severe pressures have been placed on water managers world-wide as many river basins have been plagued by extreme hydrologic conditions ranging from severe droughts to catastrophic flood events. This has been compounded by rapid population and industrial growth that has placed increased stress on available water resources, creating conflicts between stakeholders for water use. In addition, rapid development has resulted in degradation of water supplies and ecosystems from municipal, industrial and agricultural pollution. The importance of sustainable management and operation of existing water projects and facilities is magnified because of political, economic and environmental obstacles to authorization of new water projects. Management of complex river basin systems requires effective decision support tools for analyzing system components in a fully integrated manner. MODSIM is presented herein as a comprehensive decision support system for coordinated operation of multipurpose reservoir systems, conjunctive surface and groundwater management, and water quality management, with full consideration of legal and administrative mechanisms governing water use.

2. REVIEW OF RIVER BASIN MANAGEMENT DECISION SUPPORT SYSTEMS

Klein and Methlie (1995) define a decision support system (DSS) as: "A computer information system that provides information in a given domain of application by means of analytical decision models and access to databases, in order to support a decision maker in making decisions effectively in complex and ill-structured tasks." A river basin...
management DSS should have general applicability and not be hardwired to a particular river basin configuration and management structure. All of the following interactive modules must be included for categorization as a DSS: (1) dialog subsystem; (2) database management subsystem; and (3) model base management subsystem. River basin management DSS’s are designed to aid stakeholders in developing a shared vision of planning and management goals, while gaining a better understanding of the need for coordinated operations in complex river basin systems that may impact multiple jurisdictional entities. They allow evaluation of hydrologic, economic, environmental, and institutional/legal impacts as related to alternative development and management scenarios.

The more robust river basin DSS’s can provide both a planning framework for integrated river basin development and management, as well as aid in real-time river basin operations and control. Although some river basin DSS’s are suitable for flood control operations, emergency flood conditions or disaster management generally require more detailed hydraulic and contaminant transport models operating over short time steps of an hour or less.

MIKE BASIN (DHI Water & Environment, 2006), IQQM (New South Wales Department of Infrastructure, Planning and Natural Resources, Australia; Hamed and O’Neill, 2005), RIBASIM (Delft Hydraulics, 2006), IRAS (Resource Planning Associates, Inc.), and WEAP (Stockholm Environmental Institute-Boston; Yates, et al. 2005) are popular river basin management DSS’s that have been implemented world-wide in a large number of river basin systems and incorporate most of the desirable attributes of a DSS. As valuable as these DSS’s have been for many applications, each lacks effective customization capability, which limits their adaptability to unique river basin conditions, particularly with respect to complex administrative rules and policies.

As described in Draper, et al. (2004), CALSIM was developed by the California Department of Water Resources as a generalized river basin management DSS. Its specific application to joint operation of the Federal Central Valley Project (CVP) and the California State Water Project (SWP) is embodied in CALSIM II. CALSIM allows customized specification of objectives and constraints in strategic planning and operations without the need for reprogramming of complex models through use of an English-like modeling language called WRESL (Water Resources Engineering Simulation Language). CALSIM lacks a comprehensive graphical user interface for constructing and editing the river basin system topology, as well as effective mechanisms for considering conjunctive use of surface and groundwater resources. Computations in CALSIM are confined to monthly time steps without consideration of flow routing, and CALSIM is ill-suited for evaluating legal issues related to water and storage rights for priority-based water allocation.

RiverWare is a river basin modeling system under development since 1990 at the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES), University of Colorado (Zagona, et al., 2005). RiverWare is customized using the RiverWare Policy Language (RPL) for developing operational policies for river basin management and operations. A rule editor allows users to enter logical expressions in RPL defining rules by which objects behave, as well as interrelationships between objects for simulating complex river basin operations. As an interpreted language, RPL is far less computationally efficient than compiled code. Extensive, complex rule bases are required for priority-based water allocation in a river basin, and RiverWare is deficient in stream-aquifer management tools for conjunctive use of surface and groundwater resources.

WaterWare was developed through a European collaborative effort involving universities, research institutes, and commercial companies (Jamieson and Fedra, 1996). WaterWare is designed as a comprehensive decision support system for river basin planning that combines advanced technologies including geographic information systems, database technology, modeling techniques, optimization algorithms, and expert systems. WaterWare also utilizes rule-base concepts for developing operating criteria and policies, but is a proprietary modeling system requiring expensive licensing. Although WaterWare must be installed on UNIX workstations, a web based client-server implementation allows access by users on Windows-based platforms.

3. MODSIM FEATURES

3.1 Program Structure and .NET Framework

MODSIM is a generic river basin management decision support system originally conceived in
1978 at Colorado State University (Shafer and Labadie, 1978), making it the longest continuously maintained river basin management software package currently available. MODSIM is designed for developing basin-wide strategies for short-term water management, long-term operational planning, drought contingency planning, water rights analysis and resolving conflicts between urban, agricultural, and environmental concerns. The most recent version MODSIM 8.0 is developed under the MS .NET Framework and is comprised entirely of native code written in MS Visual C++.NET (Labadie, 2005). The MODSIM graphical user interface is developed in Visual Basic.NET, and includes both native code and software requiring a developer license, but allowing free distribution of runtime applications without imposition of distribution costs or licensing requirements.

One of the greatest advantages of the .NET Framework is providing users with the ability to customize MODSIM for any specialized operating rules, input data, output reports, and access to external models running concurrently with MODSIM, all without having to modify the original MODSIM source code. Customized code can be developed in any of the several .NET languages that are freely provided with the .NET Framework. All important PUBLIC variables and object classes in MODSIM are directly accessible to the custom code, and the .NET CLR produces executable code as opposed to other applications requiring scripts to be prepared in an interpreted language such as PERL or JAVASCIPT with poorer runtime performance. A powerful GUI connects MODSIM with database management components and an efficient network flow optimization model. The objective function and all constraints on the network flow optimization are automatically constructed in the GUI, thereby relieving the user from having to acquire proficiency in optimization modeling or computer programming. Optimization of the objective function essentially provides an efficient means of assuring that all system targets and guidecurves are achieved according to user-specified priorities based on water rights or economic valuation, while insuring that water is allocated according to physical, hydrological, and institutional/legal/administrative aspects of river basin management.

3.2 MODSIM GUI Graphical User Interface

The graphical user interface (GUI) for MODSIM as shown in Figure 1 provides spatially-referenced database capabilities allowing users to create and link river basin network objects on the display, and

![Figure 1. Graphical user interface for MODSIM](image)
then populate data for that object by right-mouse click to activate the object and open its tabbed database form. GIS raster layers may be imported into the GUI as background maps for network creation. Lengthy time series data for unregulated streamflows, demands, etc., can be loaded by copying data from EXCEL™ (Microsoft, Inc.) to the MS Windows clipboard and pasting the data into the appropriate Node Properties form, or importing directly from database management systems.

The main Menu Bar for MODSIM includes items to load and save a MODSIM network, import and export data, select English or metric units, search for specific nodes and links, provide zoom control, execute the model, select and display graphs; create, edit and generate tabular reports; access various utilities, print out the network, and more. The interface contains icons in the Node Palette Window for creating storage, demand, and nonstorage (points of confluence or diversion) nodes in the network by simply dragging them into the Network Editor Window, or left-button mouse clicking on the icon and then clicking on the desired location in the Network Editor Window. Link or arc objects are created directly in the Network Editor Window by moving the cursor onto the origin node, holding down the left-mouse button, and then dragging the pointer to the desired ending node, which also sets the flow direction for that link. Links can be segmented by user specification of any number of vertices, allowing any desired link shape. Multiple links connecting the same two nodes are easily created by selecting Convert to Multilink in the context menu for any link. Tools are available for deleting or moving nodes or groups of nodes, as well as copying node attributes to any user-selected node. The Network Overview Window is useful for large networks where the display window can be panned over any portion of the network.

Selecting MODSIM > Custom Runs invokes the Custom Code Editor for creating customized versions of MODSIM developed from user-supplied code written in VB.NET or C#.NET. A convenient template is provided in the Custom Code Editor as shown in Figure 2 for guiding users in the preparation of customized code. Custom code can interface with MODSIM at any desired strategic location, including data input, execution at the start of any time step, processing at intermediate iterations, and model output. Users are provided direct access to all public variables, parameters, and object classes in MODSIM for development of knowledge-based operating rules, linkage with on-line database management systems, customized output reports, and color-coded graphical displays.

Output Control provides an extensive variety of graphical and text output options for any combinations of network objects and output data types. Retaining output results over several time steps in main memory generally results in faster execution speed, but also requires larger memory allocation. After a MODSIM run is executed, right-button mouse click on any node or link opens the context menu, but with an added item: Graph, which allows rapid display of output results. Any number of additional nodes or links can be selected, providing comparative display of output results on the same graph, as seen in Figure 3. Several networks can be opened simultaneously reflecting various planning and management scenarios, with results easily compared, including probabilistic flow duration curves and various statistical measures including reliability, resiliency, and vulnerability.
3.3 Network Flow Optimization in MODSIM

The basic principle underlying MODSIM is that most physical water resource systems can be accurately simulated as capacitated, directed flow networks. The term capacitated refers to imposition of upper and lower bounds on all flows in the network, whereas directed refers to apriori specification of flow direction. In a directed network, directionless flow links are simulated by connecting two nodes with two directed arcs, each flowing in the opposite direction. Components of the system are represented as a network of nodes, both storage (i.e., reservoirs, groundwater basins, and storage right accounts) and non-storage (i.e., river confluences, diversion points, demand locations, streamflow gaging stations, return flow locations, etc.), and links or arcs (i.e., canals, pipelines, natural river reaches, and decreed water rights) connecting the nodes. Since all inflows, demands, system gains and losses must accumulate at nodes, increasing the density of nodes in the network thereby increases simulation accuracy. Although MODSIM is primarily a simulation model, the network flow optimization provides an efficient means of assuring allocation of flows in a river basin in accordance with specified water rights and other priority rankings, including economic valuation.

MODSIM simulates water allocation mechanisms in a river basin through sequential solution of the following network flow optimization problem for each time period \( t = 1, \ldots, T \):

\[
\text{minimize } \sum_{\ell \in A} c_{\ell} q_{\ell} \quad (1)
\]

subject to:

\[
\sum_{i \in F_i} q_i - \sum_{k \in L_i} q_k = b_{\ell}(q) \text{ for all nodes } i \in N \quad (2)
\]

\[
l_{\ell}(q) \leq q_{\ell} \leq u_{\ell}(q) \text{ for all links } \ell \in A \quad (3)
\]

where \( A \) is the set of all links in the network; \( N \) the set of all nodes; \( F_i \), the set of all links originating at node \( i \) (i.e., outflow links); \( L_i \) the set of all links terminating at node \( i \) (i.e., inflow links); \( b_{\ell} \) is the (positive) gain or (negative) loss at node \( i \) at time \( t \); \( q_{\ell} \) is flow rate in link \( \ell \); \( c_{\ell} \) are costs, weighting factors, or water right priorities per unit flow in link \( \ell \); and \( l_{\ell} \) and \( u_{\ell} \) are lower and upper bounds, respectively, on flow in link \( \ell \) at time \( t \). Allowing arc parameters \( l_{\ell}, u_{\ell} \) and node supplies \( b_{\ell} \) to vary as functions of network flow vector \( q \) introduces non-network constraints into the problem. These nonlinearities are due to reservoir surface area dependent calculation of evaporation, groundwater return flows, channel losses, instream flow requirements, and equitable flow distribution to demands not governed by water rights or other priorities. A successive approximations solution procedure is adopted whereby an initial set of flows \( q \) are assumed, resulting in initial estimates of flow-dependent parameters \( b_{\ell}, l_{\ell}, u_{\ell} \) Eqs. 1-3 are then solved with the Lagrangian relaxation algorithm RELAX-IV (Bertsekas and Tseng, 1994), which is up to two orders of magnitude faster than the revised simplex method of linear programming. The flows \( q \) produced from this solution then serve to update estimates of parameters \( b_{\ell}, l_{\ell}, u_{\ell} \), and the network flow optimization repeats until convergence.

4. HYDROLOGIC AND ADMINISTRATIVE COMPONENTS

4.1 Reservoir Data and Operations

The tabbed Reservoir Node Properties form (Figure 1) allows specification of reservoir capacity, storage targets, area/capacity/head/hydraulic outlet capacity tables, net evaporation rates, seepage rates, and power plant information. Hydropower generation capacity and energy production is based on power plant efficiencies varying with flow, head, and load factor. On-peak vs. off-peak and firm vs. secondary energy calculations are performed, including tailwater effects and head-dependent hydraulic capacity restrictions on reservoir discharge.

Reservoir priority numbers are entered into the General Tab of the Reservoir Node Properties Form and translated into negative costs on each link in Eq. 1, where minimization of negative costs is equivalent to maximizing flows to the higher ranked water uses. Rather than absolute values, it is the relative order of the ranking that determines allocation of network flows. However, using the Reservoir Balancing Table under the Targets tab of the Reservoir Node Properties form, several storage zones in a reservoir can be defined to allow balancing of storage allocation in a multi-reservoir system (Figure 4).
Operating rules on reservoir regulation and can be conditioned on user-defined system hydrologic state information for the current period, which can include flow forecast information (Figure 5). Hydrologic states can be based on any desired number of flow and storage conditions in the basin, and users may specify several hydrologic state indices. More complex reservoir operating rules can be developed using the customization capabilities of MODSIM.

### 4.2 Consumptive and Instream Flow Demands

Figure 6 displays the Demand Node Properties form for specification of consumptive or instream flow (flow-through) demands by input of time series data, watching flows in links in other portions of the basin, or specifying exchange credit nodes. A highly functional watch logic calculator included in MODSIM offers several algebraic and logical operators allowing user-specified water allocation rules based on flow and storage conditions anywhere in the river basin network. Exchange credit nodes can also be specified whereby deliveries to other demand nodes are dynamically assigned as demands at any node. These features provide flexibility in tying physical operations or water supply accounting for a node to conditions and operations in other parts of the network. The flow-through demand construct also allows flows to be distributed according to fixed percentages if desired. As with reservoir operating rules, demands may also be conditioned on hydrologic state indices, as in Figure 5. Although priority rankings are also assigned to all demands, shortage rules can be defined for equitably distributing supplies over a basin during low-flow or drought conditions, rather than flow distribution based solely on water rights or priorities.

### 4.3 Stream-aquifer Modeling in MODSIM

MODSIM includes modeling capabilities for conjunctive use of surface water and groundwater and simulation of stream-aquifer interactions. A stream-aquifer model based on the USGS sdf approach is included, as well as possible linkage with external groundwater models. A GIS tool called MAPSIM (Figure 7) is provided with MODSIM for processing of spatially distributed stream-aquifer response functions obtained from 3-D numerical groundwater flow models such as MODFLOW (Harbaugh, et al., 2000). MAPSIM automatically loads the processed stream-aquifer lag factors into the MODSIM database. The MODFLOW developed response coefficients provide realistic stream-aquifer response characteristics much as if MODFLOW was executed simultaneously with MODSIM, but at considerably less computational expense. Fredericks, et al. (1998) successfully linked MODSIM to MODFLOW in the South Platte River basin through generation of stream-aquifer system lag coefficients.

### 4.4 Water Quality Modeling and MODSIM

Although lacking an internal water quality model, the ease of customizing MODSIM facilitates linkage with a wide range of external models. de Azevedo, et al. (2000) integrated MODSIM with the QUAL2E-UNCAS stream water quality model for evaluating strategic planning alternatives for meeting transbasin diversion requirements for São Paulo, Brazil intrabasin water supply needs, and acceptable water quality according to various
reliability criteria. Batch processing was applied to automating the conversion and transfer of MODSIM network flow results for input to QUAL2E-UNCAS. This environment allowed adjustment of operating targets and priorities in MODSIM to achieve integrated water quantity and quality objectives.

Dai and Labadie (2001) applied MODSIM to the Lower Arkansas River Basin, Colorado for identifying opportunities to improve water quality through conjunctive use of surface and groundwater. The QUAL2E streamflow quality model and a groundwater return flow salinity model are executed at each MODSIM simulation time step. SIAM (System Impact Assessment Model), developed for the Klamath River basin, Oregon and California by the U.S. Geological Survey and the U.S. Bureau of Reclamation, links MODSIM with the HEC-5Q reservoir water quality model, an aquatic habitat model, and the SALMOD fish production model (Figure 8). MODSIM evaluates system operations in SIAM for improving summer/fall water quality conditions to benefit declining anadromous fish populations (Campbell, et al., 2001).

Leu (2001) applied MODSIM to the San Joaquin River Basin to investigate the use of economic-based strategies such as increased water prices, tiered water pricing structures, changes in San Joaquin River environmental flows, and changes in reservoir operations to improve water management. This study made effective use of the customization capabilities of MODSIM for modeling the complex water pricing structures in the basin. This demonstrated the capability of MODSIM to allocate flows based on economic criteria, rather than solely on water rights and priority based allocation.

5. MODSIM EXTENSIONS

5.1 Storage Rights Extension

Selection of the Storage Rights Extension in the Extensions menu item (Figure 1) displays the Storage Rights Reservoir icon in the Node Palette. Although accrual to storage account reservoirs is based on water rights, once flow has accrued, individual or group owners may receive water from these accounts based on ownership. Storage right accounting in MODSIM maintains paper accounting such that owners are limited to receive only what is available in their accounts. The procedure is flexible in that owners may actually receive physical...
water from other reservoirs. This facilitates exchange agreements between users whereby owners may utilize their accounts to exchange natural flow diversions with senior water right holders.

5.2 Backrouting Extension

MODSIM includes Muskingum-type or user-specific time-lagged hydrologic streamflow routing capabilities for daily simulation. An innovative backrouting procedure looks ahead to future time periods in order maintain appropriate reservoir operations, minimize downstream spills and shortages and assure legal water allocation under water rights with consideration of time lag delays in delivering releases to downstream water users. Any link can be specified as a routing link. For details on backrouting, see Labadie and Larson (2006).

5.3 Water Rights Extension

Selection of the Water Rights Extensions creates the Water Rights Control menu item under MODSIM, which activates the Water Rights Priorities–Extension form. Complex water rights data bases as MS ACCESS *.mdb files can be imported, along with tools for creating additional water rights and editing existing rights. This tool automatically assigns water rights data to the appropriate nodes and links in the network, thus greatly facilitating any priority-based water allocation in the network.

6. GEO-MODSIM

GEO-MODSIM is a full implementation of MODSIM 8.0 that operates as a custom extension in ArcGIS (ESRI, Inc.), allowing automatic generation of MODSIM networks from geometric networks and processing of spatial database information for MODSIM network features (Figure 9). GEO-MODSIM networks can be developed, edited, executed, and output results displayed completely within the ArcMAP interface for ArcGIS.

![Figure 8. SIAM interface (Bartholow, et al., 2005)](image-url)
7. APPLICATION OF MODSIM TO THE IMPERIAL IRRIGATION DISTRICT WATER TRANSFER STUDY

Miller, et al. (2005) describe application of MODSIM to analysis of the water transfer agreement between the Imperial Irrigation District (IID) and the San Diego Water County Water Authority in Southern California. Over 3 million acre feet of Colorado River flow is diverted annually to the All American Canal, the largest irrigation canal in the world. Since IID farmers receive the great majority of these flows, MODSIM is applied to identifying opportunities for water conservation in the IID that can generate up to 370 million m$^3$ per year of transferable flow to the large urban areas of Southern California. The IID includes over 2000 km$^2$ of irrigated farmland served by 2736 km of canals and laterals distributing flow to 5300 farm delivery gates. The high efficiency of the MODSIM solver allows fully integrated modeling of the IID network, comprising over 10,000 nodes and links. MODSIM is an invaluable evaluation tool for stakeholders, which include IID farmers, the San Diego County Water Authority, and environmental interests concerned about impacts of the conservation plan on drainage quantity and quality to the Salton Sea. In addition to conservation planning, MODSIM is also being configured to provide daily, and possibly hourly, real-time regulation guidance for automated control of gates in the IID system.

8. REFERENCES


Bertsekas, D. and P. Tseng, RELAX-IV: A faster version of the RELAX code for solving minimum cost flow problems, Computation...


