MODSIM 8.1: River Basin Management Decision Support System

User Manual and Documentation

contacts:

John W. Labadie
Department of Civil and Environmental Engineering
Colorado State University
Ft. Collins, CO 80523-1372
email: labadie@engr.colostate.edu

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I. INTRODUCTION

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. The most recent version MODSIM 8.1 is developed under the Microsoft .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.

MODSIM is designed as a generalized river basin management decision support system (DSS) designed as a computer-aided tool for developing improved basin wide and regional 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. Sprague and Carlson (1982) defined a DSS as *"an interactive computer-based support system that helps decision makers utilize data and models to solve unstructured problems."* A DSS integrates the following interactive subsystems: (1) model base management subsystem; (2) database management subsystem; and (3) dialog generation and management subsystem. As illustrated in Fig. 1, MODSIM embodies all essential components of a decision support system.

The graphical user interface (GUI) connects MODSIM with the various database management components and an efficient network flow optimization model. The objective function and constraints of the network flow optimization model are automatically constructed using parameters specified with the GUI without requiring any background in optimization or computer programming by the user. Optimization of the objective function essentially provides an efficient means of achieving system targets, demands and guidecurves according to desired priorities, while assuring that water is allocated according to physical, hydrological, and institutional/administrative aspects of river basin management.

MODSIM is 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. MODSIM provides for integrated evaluation of hydrologic, economic, environmental, and institutional/legal impacts as related to alternative development and management scenarios, including the conjunctive use of surface water and groundwater resources. As a

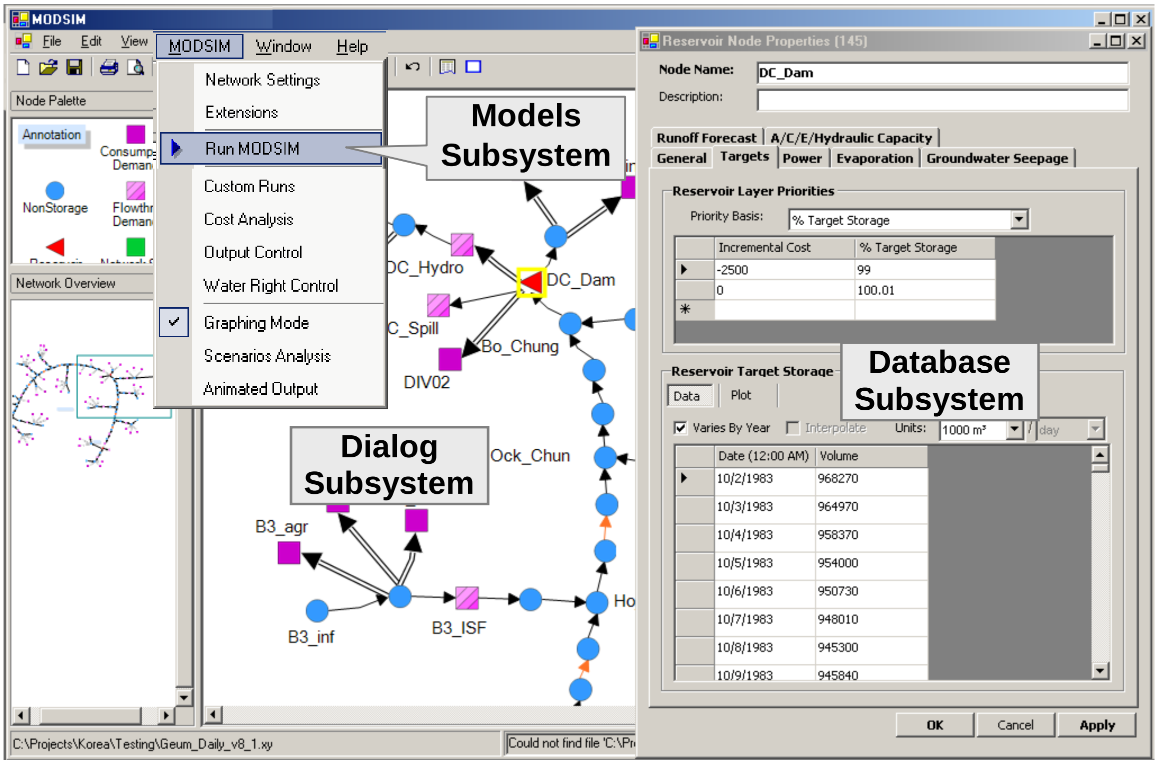


Fig. 1. MODSIM as a Decision Support System

robust river basin management DSS, MODSIM provides both a planning framework for integrated river basin development and management, as well as aid in real-time river basin operations and control. Although MODSIM is not designed for emergency flood conditions or disaster management that generally require detailed hydraulic and contaminant transport models operating over short time steps of an hour or less, operational rules can be assigned in MODSIM in support of these objectives.

II. MODSIM FEATURES AND APPLICATIONS

A. MODSIM Software Development

The MODSIM DSS operates under Microsoft Windows ME, 98, NT, 2000, or XP and is comprised entirely of native, object-oriented code written in Microsoft Visual C++.NET. The graphical user interface for MODSIM is developed in Visual Basic.NET, and includes both native code and code requiring a developer license, but allowing free distribution of runtime applications without imposing licensing requirements or any costs to the user. The Visual Studio .NET IDE facilitates development and management of large-scale applications, including improved reliability, scalability, security, and performance. The .NET Framework provides a new architecture that overcomes restrictions of COM-based technology, while still allowing COM interoperability for development of managed code that uses COM components. The .NET Framework provides a single API instead of consuming several API's such as Win32, ole32.dll, etc. Managed Code running under the Common Language Runtime (CLR) of .NET provides platform independence, language interoperability, and performance improvement.

The .NET Framework provides a powerful environment for customization of MODSIM for any unique river basin management conditions without requiring recoding of MODSIM. Customized code can be developed in any of the several .NET languages that are freely provided with .NET Framework. All 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 JAVASCRIPT with poorer runtime performance. Tutorial C associated with this User Manual and Documentation provides detailed information on development of customized code, along with a wide range of examples. MODSIM is distributed as freeware on the Internet at: http://modsim.engr.colostate.edu. The MODSIM installer provides the option of installing the Microsoft .NET Framework if it is not currently installed on the target machine. Also downloadable at this site are MODSIM user manuals, documentation, example applications, and sample data sets.

B. MODSIM Capabilities

MODSIM includes many unique features and capabilities not found in other river basin management models:

Microsoft .NET Framework. MODSIM is implemented on desktop computers operating under Microsoft Windows ME, 98, NT, 2000 or XP, and is developed under the new Microsoft .NET Framework.

Freeware. Since all components of MODSIM are developed entirely from native Visual C++.NET code, there is no need for MODSIM users to purchase expensive licenses for proprietary software.

Graphical User Interface. MODSIM employs a powerful, interactive graphical user interface (GUI) for creating, locating and connecting river basin network components, as well as a spreadsheet-style data editing capability emulating an object-oriented database management system. Time series data sets are convenient imported into MODSIM from external database management systems.

Network Flow Optimization. The basic solver in MODSIM is a state-of-the-art network flow optimization algorithm that is more than an order of magnitude faster than solvers currently in use in other river basin modeling packages and capable of modeling extremely large-scale networks.

Data-driven Model. MODSIM maintains complete reliance on user input data and specifications for describing system features, operational requirements, and priorities, which are separated from the network modeling algorithmic structure. No *a priori* defined operating policies or priorities hardwired into MODSIM.

Long-term Planning to Real-time Operations. MODSIM is applicable to long term planning (monthly), medium term management (weekly), and short term operations (daily) in river systems.

Complex River Basin Configurations. MODSIM allows simulation of a wide variety of river basin configurations and operating conditions without requiring specification of complex IF-THEN rules governing allocation of flows and storage. Complex network topologies can be constructed, including looped and bifurcating flow paths. Network topology is graphically created by simple point and click actions on the GUI palette. In addition, georeferenced network topologies can be loaded into MODSIM from a geographic information system (GIS).

Reservoir Operations and Hydropower Generation. Reservoir balancing routines are included, allowing division of reservoir storage into several operational zones for controlling the spatial distribution of available storage in a river basin. Hydropower generation capacity and energy production is based on power plant efficiencies varying with discharge and head. Energy production calculations are performed, with consideration of tailwater effects and head-dependent hydraulic capacity restrictions on reservoir discharge.

Conditional Operating Rules. Operating rules on reservoir regulation and demand allocation can be conditioned on user defined system *Hydrologic State* information for the current period, including development of shortage rules for equitably distributing water demand shortages over a basin during low-flow or drought conditions.

Watch Logic. A highly functional *watch logic* calculator in the MODSIM GUI offers several algebraic and logical operators that allows user-specified water allocation rules to be based on flow and storage conditions anywhere in the river basin network.

Conjunctive Use. 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 possible linkage with external groundwater models. A GIS tool called MAPSIM is available with MODSIM that provides processing of spatially distributed stream-aquifer response functions obtained from numerical 3-D groundwater models such as MODFLOW.

Water Rights and Storage Contracts. MODSIM is capable of directly incorporating institutional structures governing water allocation under direct flow or natural streamflow rights and seasonal storage rights and contracts, including provisions for allocating water according to specified priorities based on current river basin conditions. Other administrative mechanisms that can be modeled in MODSIM include rent pools, water banking, flow augmentation plans, and exchanges that allow flexible system operations while maintaining water rights and contract legality.

Customized MODSIM. Users can prepare customized code in the Visual Basic.NET or C#.NET languages that are compiled with MODSIM through the Microsoft .NET Framework. Users are provided access to all key variables and object classes in MODSIM, thereby allowing customization for any complex river basin operational and modeling constructs without the need for reprogramming and recompiling the MODSIM source code. Custom code can be developed for defining complex operating rules and policies, executing external modules such as water quality models, input of specialized data sets for particular applications, preparing customized model output and reports, and linking MODSIM with database management systems to provide access to timely data and forecast information for real-time river basin management.

Streamflow Routing. MODSIM includes Muskingum or user-specified time-lagged hydrologic streamflow routing capabilities for daily simulation. In addition, an innovative *backrouting* procedure is available which looks ahead to future time periods in order maintain legal water allocation under appropriative water rights.

Monte Carlo Analysis. MODSIM allows simulation of synthetic or stochastically generated inflow/demand sequences for use in Monte Carlo analysis for developing flow-duration curves and exceedance probability estimates for key variables.

Graphical Plots and Scenario Analysis. MODSIM produces graphical plots of important model time series variables reflecting system performance, as well as tabulated results showing storage levels, releases, inflows, energy generation, power capacity, system losses and spills, water deliveries, shortages, instream flow requirements, and flows in any reach of the system. Plotting packages are available for comparative evaluation of operational plans and scenarios, including display of flow-duration curves and statistical analysis.

C. Successful Applications

Since its initial development, MODSIM, from which MODSIM is adapted, has undergone dramatic improvements and updates, and has enjoyed widespread use by numerous governmental and private organizations for simulating complex river system operations in the U.S. and throughout the world. Various versions and adaptations of MODSIM have been successfully applied to a number of complex river basin systems:

Rio Grande River Basin (Graham, et al., 1986)

- ***sponsor:*** U.S. Forest Service
- ***scope :*** Entire Rio Grande River Basin in Colorado, New Mexico, and Texas
- ***monthly time step***: stream-aquifer interactions not included since focus is on incremental surface water inflows to the basin
- ***objective:*** determination of how additional flows made available through planned silvacultural activities in the Rio Grande National Forest would be allocated downstream with consideration of complex in-state water right decrees and interstate compact agreements; includes analysis of impact of possible future storage facilities

Upper Pampanga River Basin, The Philippines (Faux, et al., 1986)

- ***sponsors:*** National Science Foundation - International Programs and National Irrigation Administration, Manilla, The Philippines
- ***scope:*** Upper Pampanga River Basin covering 6700 km^2 in Central Luzon; considered the country's most important rice producing region
- ***monthly time step:*** surface water modeling only
- ***objective:*** improve operational efficiency of the Upper Pampanga River Integrated Irrigation System (UPRIIS), balance hydroelectric generation and irrigation supply, and identify bottlenecks in the water distribution network for possible expansion of canal capacity

Geum River Basin, South Korea (Labadie, et al., 2004)

- ***sponsor:*** Korea Water Resources Corporation (K-water)
- ***scope:*** entire watershed of the Geum River, Korea, including transbasin diversions to the adjacent Jun-Ju region
- ***monthly and daily time steps:*** focus on surface water allocation based on priorities for water use sectors as well equitable distribution of water within each sector; application to real-time operations
- ***objectives:*** develop a real-time decision support system for the Geum River basin that is applicable to long-term operational planning as well as daily real-time operations; inclusion of flow routing, transbasin diversions, and integrated operation of basin facilities to satisfy municipal, industrial, agricultural, energy, and instream flow demands.

Colorado-Big Thompson River System, Northern Colorado (Law and Brown, 1989)

- ***sponsor:*** Northern Colorado Water Conservancy District
- ***scope:*** both the West Slope and East Slope components of the Colorado-Big Thompson (C-BT) project of Northern Colorado
- ***monthly time step:*** surface water modeling only
- ***objective:*** fully integrated operations of the C-BT/Windy Gap system and portions of the Cache La Poudre River Basin; predict the yield of a proposed reservoir on the Cache La Poudre River and investigate various management options

Lower Nile River Basin, Egypt (El-Beshri and Labadie, 1994)

- ***sponsors:*** Egyptian Ministry of Public Works and Water Resources and USAID
- ***scope:*** Lower Nile River, including the Nile Delta
- ***monthly time step:*** both surface water and groundwater modeling
- ***objective:*** investigate the conjunctive use of surface water and groundwater in the Lower Nile Basin in order to reduce pressure on the High Aswan Dam for meeting current and future water supply requirements.

San Joaquin River, Central Valley, California (Marques, et al. 2006)

- ***sponsor:*** U.S. Bureau of Reclamation, Mid-Pacific Region, Sacramento, California
- ***scope:*** San Joaquin River Basin (1,638 mi^2), California
- ***monthly time step:*** includes conjunctive use of groundwater and surface water; economic-based allocation of water resources
- ***objective:*** investigate the use of economic-based strategies such as increased water prices, tiered water pricing, changes in San Joaquin River environmental flows, and changes in reservoir operations and groundwater basin extractions to improve water management

Gunnison River Basin, Colorado (Weiss, et al., 1997)

- ***sponsor:*** Colorado Department of Water Resources
- ***scope:*** Gunnison River Basin, tributary to the Colorado River
- ***monthly time step:*** surface water modeling only; complex administrative issues
- ***objective:*** environmental impact evaluation of proposed AB Lateral Hydropower Facility, Montrose Colorado; fully integrated modeling of entire river basin including consideration of over 1000 water rights and complex exchange agreements

South Platte River Basin, Colorado (Fredericks, et al., 1998)

- ***sponsor:*** Colorado Water Resources Research Institute
- ***scope:*** Lower South Platte River Basin, Colorado
- ***monthly and daily time steps:*** conjunctive use of groundwater and surface water; integration of MODSIM and MODFLOW groundwater model; integration of MODSIM and GIS
- ***objective:*** analysis of groundwater augmentation plans to replace depletions that would otherwise accrue to the South Platte River as a result of well pumping used to meet irrigation demands

Lower Arkansas River Basin, Colorado (Kastner, 2001)

- ***sponsor:*** Office of the Colorado State Engineer
- ***scope:*** Lower Arkansas River Basin below Pueblo Dam, Colorado
- ***daily time step***
- ***objective:*** evaluation of the Winter Water Storage Program for allocating and storing winter season water supplies in the Arkansas River basin among water users who formerly used these waters for direct flow winter irrigation; the stored waters are later used more effectively and efficiently during the following irrigation season.

Lower Arkansas River Basin, Colorado (Dai and Labadie, 2001; Triana, et al., 2006)

- ***sponsor:*** Colorado Water Resources Research Institute
- ***scope:*** Lower Arkansas River Basin below Pueblo Dam, Colorado
- ***monthly time step:*** conjunctive use of groundwater and surface water; integration of water quality and water quantity modeling with MODSIM.
- ***objective:*** Determine opportunities for improving water quality in the Lower Arkansas River Basin through conjunctive use of groundwater and surface water

Imperial Irrigation District, California (Miller, et al., 2005)

- ***sponsor:*** Imperial Irrigation District (IID), El Centro, California
- ***scope:*** District irrigated area of over 460,000 acres; average annual flow of 3,000,000 ac-ft diverted by IID at the All American Canal
- ***monthly and daily time step*:** MODSIM network models 230 miles of main canal, 1,440 miles of secondary canals and laterals, and 5,590 delivery gates; applied to both the water distribution system and the irrigation drainage system; MODSIM network composed of over 10,000 nodes and links; integration of water quality models into MODSIM to assess impacts of water conservation programs on drainage water quality, which impacts the nearby Salton Sea
- ***objective:*** apply MODSIM to assessing both the water quantity and quality impacts of voluntary conservation programs that could provide transfer of up to 300,000 ac-ft of water to metropolitan areas of Southern California

Upper Snake River Basin, Idaho (Larson and Spinazola, 2000; Miller, et al., 2003)

- ***sponsor:*** U.S. Bureau of Reclamation, Pacific Northwest Region
- ***scope:*** Upper Snake River Basin, Idaho
- ***monthly time step*:** conjunctive use of groundwater and surface; integration of MODSIM and MODFLOW groundwater model
- ***objective:*** quantification of impacts to irrigation water supply, river and reservoir recreation, resident fish and wildlife, and other local water uses from various proposed storage rental and reallocation scenarios for satisfying instream flow requirements for endangered species.

Piracicaba River Basin, Brazil (de Azevedo, et al., 2000)

- ***sponsor:*** National Council of Science and Technology, Brazil
- ***scope:*** Piracicaba River Basin (12,400 km^2), State of Sao Paulo, Brazil
- ***monthly time step:*** integration of water quantity and quality modeling; Monte Carlo analysis and evaluation of risk measures
- ***objective:*** joint application of MODSIM and the QUAL2E-UNCAS stream water quality model for evaluation of strategic planning alternatives for meeting transbasin diversion requirements for the city of Sao Paulo, intrabasin water supply needs, and acceptable water quality according to various reliability criteria

Deschutes River Basin, Oregon (La Marche, 2001)

- ***sponsors:*** Oregon Water Resources Department and U.S. Bureau of Reclamation
- ***scope:*** Upper and Middle Deschutes Basin and Crooked River Basin; includes two major reservoirs: Wickiup (200,000 ac-ft) and Crane Prairie (55,800 ac-ft); beneficial uses primarily irrigation (100,000 acres of irrigated lands), recreation, fish and wildlife maintenance, and flood control
- ***monthly time step:*** focus on maintaining instream flow uses for environmental and ecological purposes
- ***objective:*** optimal allocation of water in the Deschutes River Basin to satisfy both irrigation demands and instream flow requirements

Klamath River Basin, Oregon and California (Campbell, et al., 2001)

- ***sponsor:*** U.S. Geological Survey, Biological Resource Division
- ***scope:*** Klamath River Basin from Keno, Oregon to Seiad Valley, California
- ***monthly and daily time step:*** integration of MODSIM with HEC-5Q water quality model
- ***objective:*** integrated application of MODSIM and HEC-5Q to explore potential for changing system operations to improve summer/fall water quality conditions to benefit declining anadromous fish populations

Little Butte and Bear Creek River Basins, Oregon (Stillwater, 2003)

- ***sponsor:*** U.S. Bureau of Reclamation, Pacific Northwest Region
- ***scope:*** Little Butte and Bear Creek Rivers, tributary to the Rogue River, Oregon (includes over 37,000 acres of irrigated lands); includes transbasin diversions from the Klamath River Basin
- ***monthly time step:*** separates USBR project water from natural flow rights and includes numerous storage accounts in several reservoirs in the basins.
- ***objective:*** apply MODSIM for the Little Butte/Bear Creeks Management Project Steering Committee to demonstrate the effects of saved water and alternative and supplemental water supplies. The irrigation districts and other local irrigators, the State water master, and technical specialists from Federal and State natural resource agencies, provided direction and input for MODSIM network development.

Payette River Basin, Idaho (Stillwater, 2004a)

- ***sponsor:*** U.S. Bureau of Reclamation, Pacific Northwest Region
- ***scope:*** physical and operational characteristics of reservoirs, river reaches, and diversions of the Payette River system; reservoirs modeled include Cascade Reservoir, Deadwood Reservoir, Payette Lake and the Upper Lakes, and Black Canyon Reservoir.
- ***monthly time step:*** historical streamflow record extending from 1928 to present
- ***objective:*** determine the impacts of streamflow augmentation for endangered species on existing irrigation water supplies.

Tualatin River Basin, Oregon (Stillwater, 2004b)

- ***sponsor:*** U.S. Bureau of Reclamation, Pacific Northwest Region
- ***scope:*** Tualatin River Basin (700 mi^2 drainage); includes U.S. Bureau of Reclamation projects Barney Reservoir (20,000 ac-ft) and Hagg Reservoir (53,640 ac-ft), providing water for irrigation, municipal supplies, stream quality, flood protection and recreational benefits.
- ***monthly time step:*** includes conjunctive use of groundwater and surface water
- ***objective:*** demonstrate the effects of Reclamation's current operations in the Tualatin Basin

Location maps (images captured from Google Earth™) of these river basins where various versions of MODSIM has been successfully applied to a wide variety of problems in river basin water management are shown in Fig. 2. In addition to these applications, MODSIM is serving as a valuable water supply planning tool for several municipalities, including the City of Colorado Springs, Colorado (*contact:* Brett Gracely, Water Resources Planning Supervisor, Colorado Springs Utilities), the City of Ft. Collins, Colorado (*contact:* Dennis Bode, Water Resources Manager, City of Ft. Collins), and the City of Greeley, Colorado (*contact:* Todd Williams, Water Resources Manager, City of Greeley).

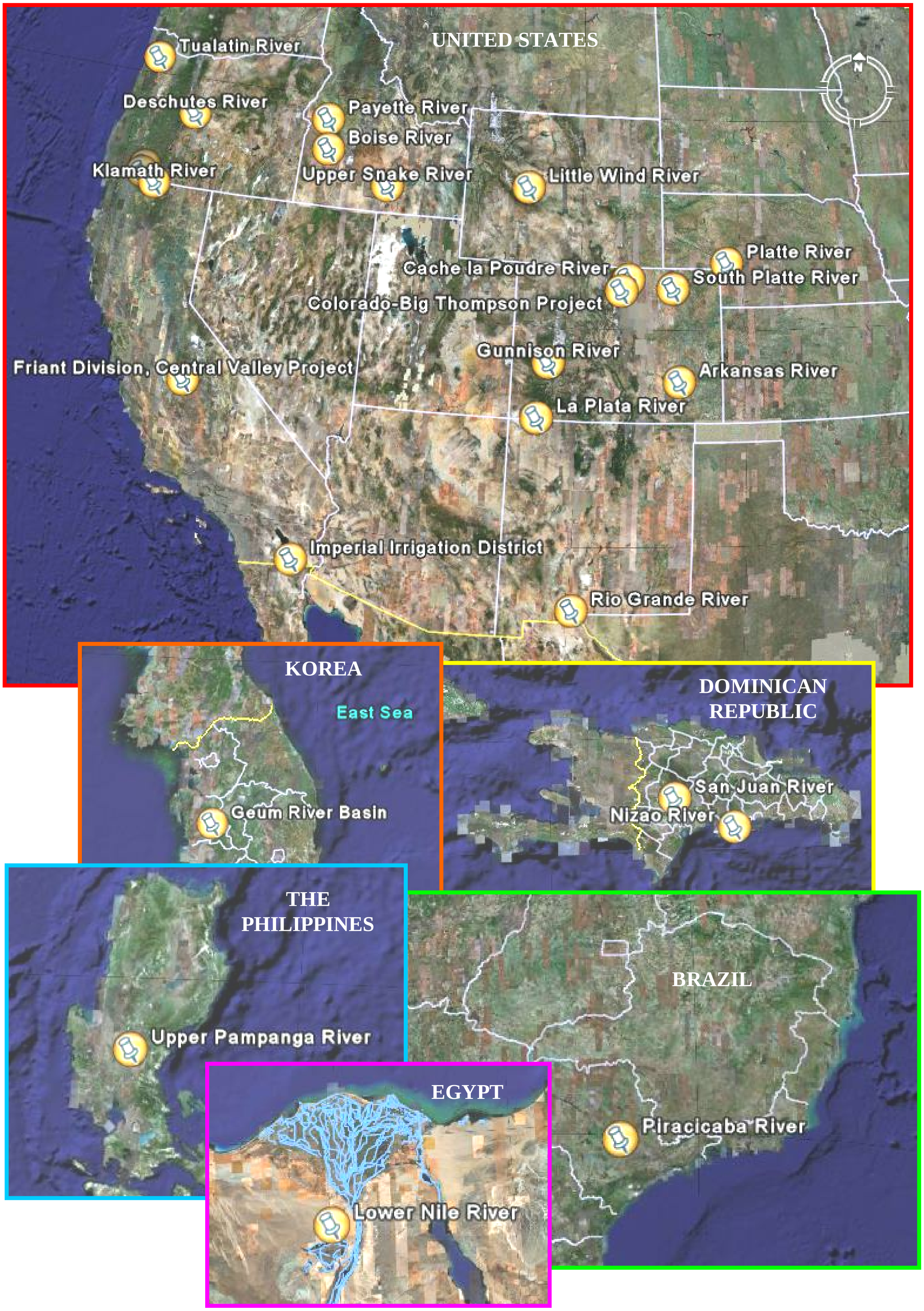


Fig. 2. Locations of successful applications of MODSIM to river basin management.

III. RIVER BASIN NETWORK DEVELOPMENT IN MODSIM

A. Network Flow Approach to River Basin Modeling

The basic principle underlying MODSIM is that most physical water resource systems can be simulated as *capacitated* flow networks. The term capacitated refers to imposition of strict upper and lower bounds on all flows in the network. 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, and demand locations), and *links* or *arcs* (i.e., canals, pipelines, natural river reaches, and decreed water rights) connecting the nodes (Fig. 2). 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.

A network formulation of a river basin system provides a physical picture revealing the morphology of the system that is readily recognizable. In effect, the graphical network links are the model decision variables. Network optimization techniques are specialized algorithms that perform integer-based calculations on linear networks that are considerably more efficient than real number computations and matrix operations employed in standard linear programming codes based on extensions of the revised simplex method. Integer-based calculations are not a disadvantage since appropriate scaling of link flows can produce solutions for any desired order of accuracy. The high efficiency of network flow optimization algorithms allows rapid solution of large-scale networks comprising thousands of nodes and links on desktop computers. This also makes it feasible to perform several iterative solutions so as to consider certain nonlinear or dynamic system features.

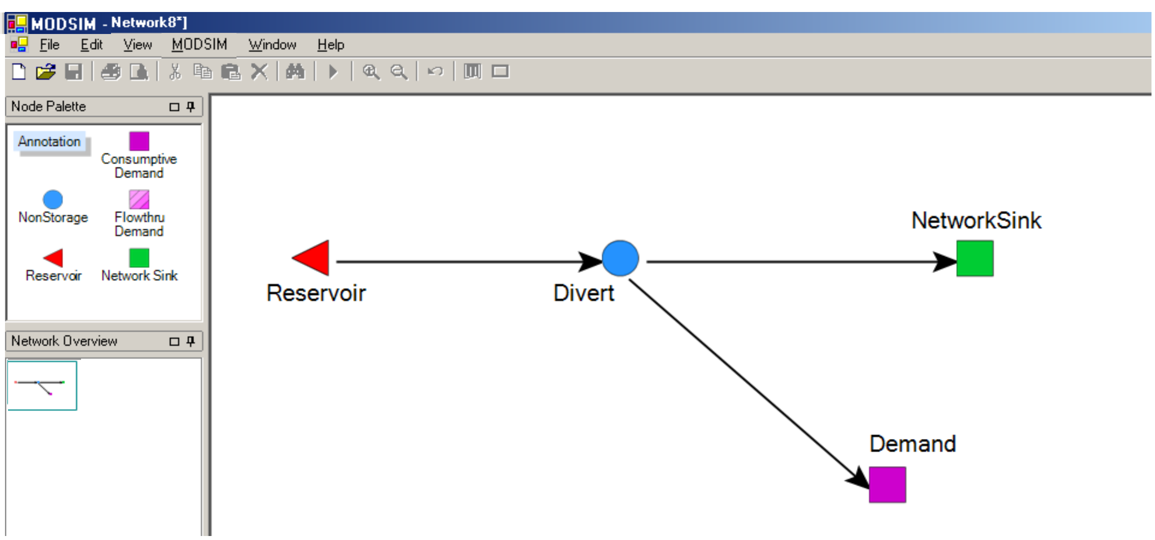


Fig. 2. Node and link objects in MODSIM

Important *assumptions* associated with MODSIM are listed as follows:

- All storage nodes and linkages are bounded from below and above (i.e., minimum and maximum storage and flows are given, with the latter allowed to vary over time.
- Each linkage must be unidirectional with respect to positive flow; flow reversals can be modeled by assigning an additional reverse direction link between two nodes.
- All inflows, demands, system gains and losses must accumulate at nodes; increasing the density of nodes in the network thereby increases simulation accuracy, but also increases computer time and data requirements.
- Each reservoir is designated as a spill node for losses from the system proper. Spills from the system are the most expensive type of water transfer, such that the model always seeks to minimize unnecessary spills. Spills may be retained in the network by specification of an additional release link from a reservoir which can be labeled as a high cost link.

B. MODSIM GUI for Network Creation and Editing

The graphical user interface (GUI) for MODSIM as shown in Fig. 3 provides spatially-referenced database capabilities allowing users to create and link river basin network objects on the display, and then populate data for that object by right-mouse click to activate the object and open a database form associated with that object. Lengthy time series data for streamflows, demands, etc., can be imported from Excel (*.xls), Access (*.dbf) or comma-separated ASCII files (*.csv), or by copying data into the Windows Clipboard and pasting into the appropriate **Node Properties** form. Time series data can

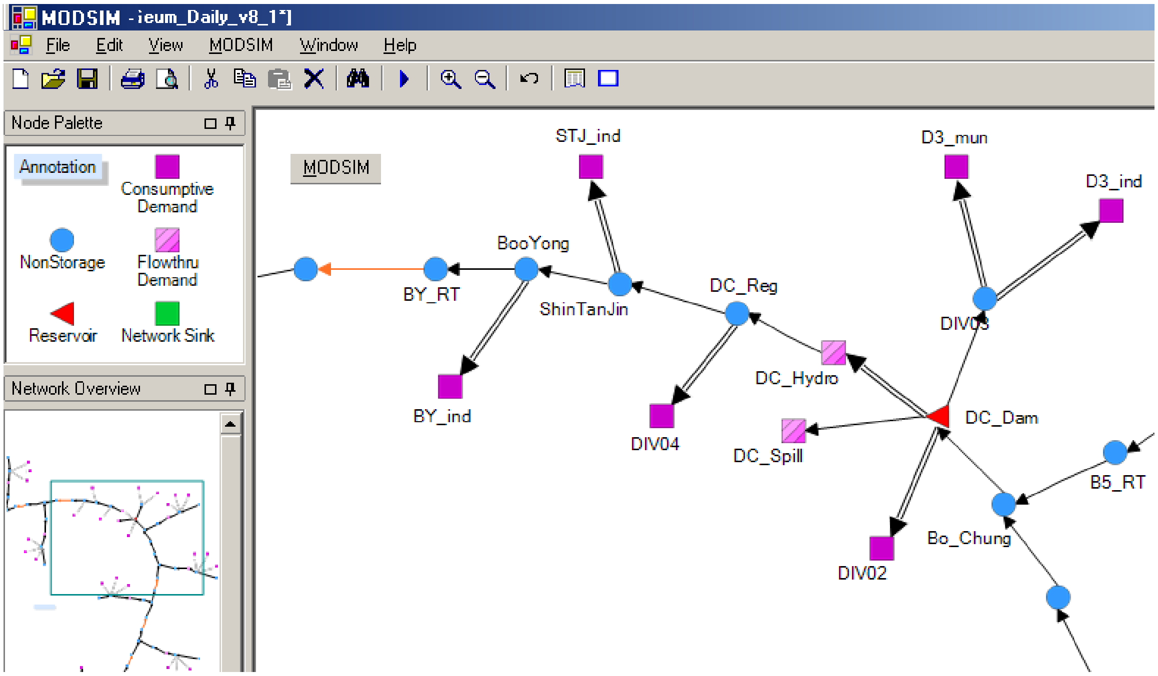
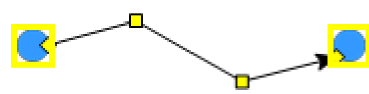


Fig. 3. Graphical user interface for MODSIM

also be loaded automatically through development of custom code, as discussed subsequently. All MODSIM input data are stored in a command-oriented ASCII text file ***.xy** where each line of input begins with a command that the input parsing code associates with a model construct, with data values relevant to the modeled feature following the command.

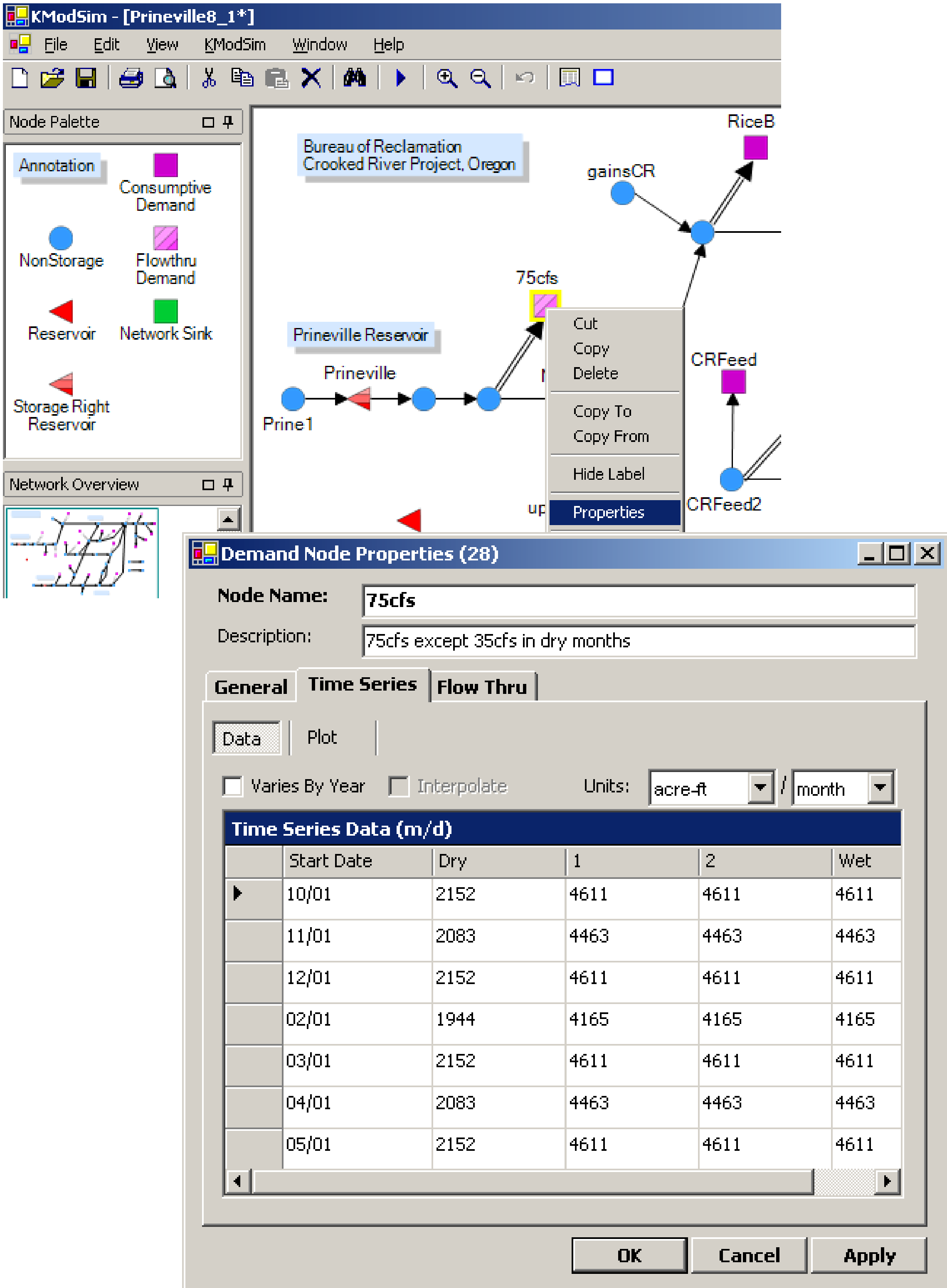
The main *Menu Bar* for MODSIM is located at the top of the *Network Editor Window* in the interface, along with a *Toolbar* below the *Menu Bar* with single click access to several menu items. The menu items are used to load and save a MODSIM network, import and export data, select English or metric units, search for specific nodes and links, run 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 various types of 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*. Links or arcs are created in the *Network Editor Window* by moving the cursor onto the origin node until a *pointing hand* icon appears, 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. The *Network Overview Window* is useful for large networks where the display window of any size can be panned over any portion of the network.

Clicking on any node object in the *Network Editor Window* makes that object *active*, which is indicated by the node being highlighted in a yellow box. Once a node is located in the *Network Editor Window*, it can be easily moved by *left-button mouse click and hold*, and then dragging it to the desired location. All links connected to that node will be moved along with the node. Groups of node and links can be moved together by *left-button mouse click and hold* and dragging a rectangular area encompassing the groups of nodes and links to be moved, with selected nodes highlighted in yellow boxes and selected links highlighted with yellow break points. Any actions within the *Network Editor Window* can be undone by the user by selecting **Edit > Undo** in the *Main Menu Bar*.



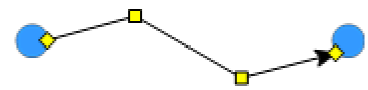
Right-button mouse click on any node in the *Network Editor Window* displays a context menu with several items. **Cut** allows the node to be deleted and pasted at another location, whereas **Delete** removes the node without paste retrieval. **Copy** retains the node and creates a copy that users can **Paste** (with or without data) to any location in the Window. **Copy To** allows all of the attributes of the selected node to be copied to another user-specified node, whereas **Copy From** allows all properties of another node to be copied to the current selected node. **Hide Label** is useful for removing excess notation in the *Network Editor Window* for nodes where labels are not important for display. Selecting **Properties** opens the database form for that node, allowing the user to enter and edit all of the data and attributes associated with that object. The **Properties** form can also be directly activated by double clicking on the node object.

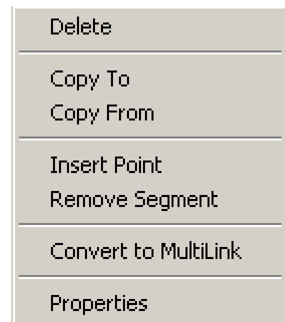
For example, selecting **Properties** for the flow-through demand *75cfs* in the *Prineville* network below (Crooked River basin, Oregon) displays its tabbed **Node Properties** form, allowing manual entry, import (by cut and paste), and editing of all data associated with that network object.



After a MODSIM run is executed, *right-button mouse click* on a node again opens the context menu, but with an added item: **Graph**, which allows rapid display of output results.

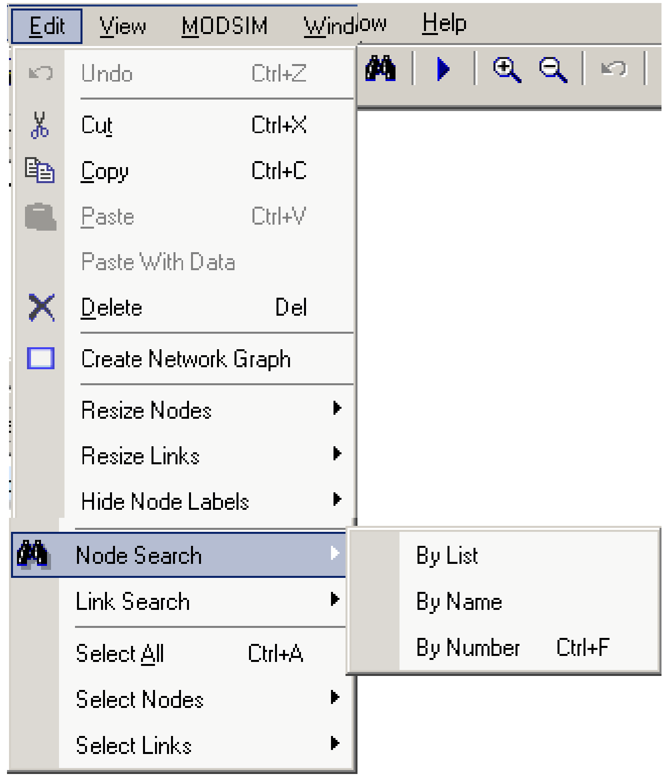
Clicking on any link object in the *Network Editor Window* makes that object *active*, which is indicated by display of yellow square-shaped *break point markers* along the link, as well as yellow diamond-shaped markers at the link beginning and end points. *Break points* can be moved by simply clicking on them and dragging, thereby allowing users to change the shape of the link. By default, when a link is first created a single *break point* is inserted in the center of the link, but additional break points can be inserted by the user. Similar to nodes, *right-button mouse click* on links also opens a context menu with items **Delete, Copy To**, **Copy From**, **Insert Point**, **Remove Segment**, **Convert to MultiLink**, and **Properties**. Similar to the node context menu, once a MODSIM run is completed, the **Graph** item is added to the link context menu.



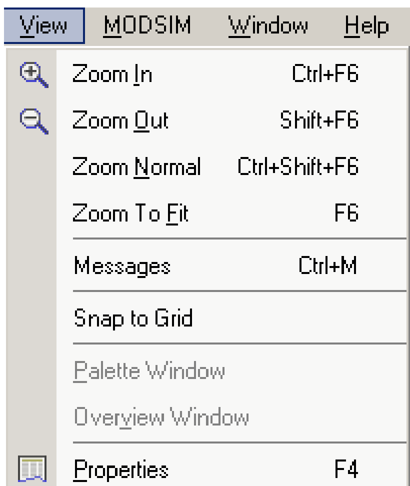


Insert Point allows users to introduce additional *break points* in the link, thereby changing its shape as connected line segments. **Remove Segment** performs the opposite operation by removing any segment. **Convert to MultiLink** allows the user to specify any desired number of separate links connecting the same two nodes, and **Properties** opens the database form, allowing the user to enter and edit all data and attributes associated with that link object. Once a link object is converted to a *MultiLink*, it is displayed as a double arrow in the *Network Editor Window*. In addition, for simulations using a daily time step, any link can be specified as a **channel routing link** in the **Link Properties** form, which changes the color of the link to orange. As with nodes, the **Link Properties** form can also be directly activated by double clicking on the link object. Similar to the **Node Properties** form, the **Link Properties** form is tabbed for each data category, with spreadsheet-style data entry for tabular data.

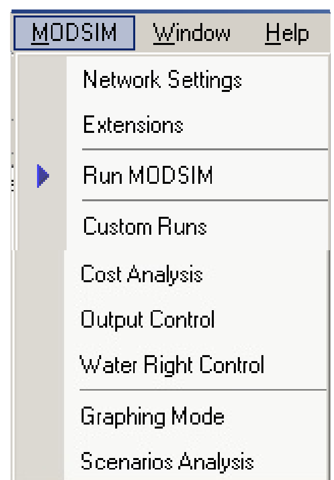
Under the **Edit** *Pull-Down Menu*, a number of useful operations on network objects are available, such as **Undo**, **Cut**, **Copy**, **Paste**, **Delete**, **Resize Nodes** and **Links**, **Node** and **Link Search**, and various **Select** options. Various tools such as **Resize Node**, **Resize Links**, and **Hide Node Labels** provide the user with various options for changing the network display. **Node Search** and **Link Search** is particularly useful for large networks, where a particular node and link can be selected from a scrollable list or directly entered by name or number, where each network object created in MODSIM is automatically assigned a unique number. The network display then shifts to the region surrounding the selected node or link, which is highlighted as an active object. **Select Nodes** and **Select Link** is useful for output of results for only those objects of interest in the simulation.



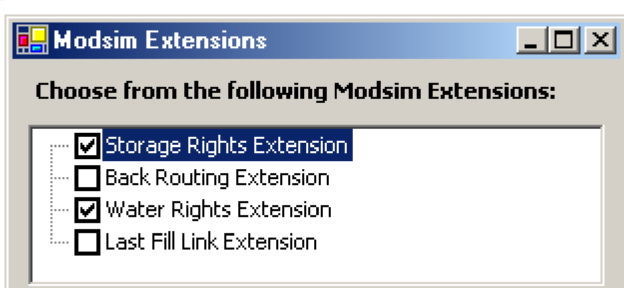
The **View** *menu* on the *Main Toolbar* provides additional features, including **Zoom** control, **Messages** displaying of information on the status of the MODSIM run, and **Snap to Grid**, which when activated, snaps created or moved objects in the *Network Editor Window* to a finite grid for ease of alignment of objects. Un-checking **Snap to Grid** allows objects to be moved to any location in the *Window*.

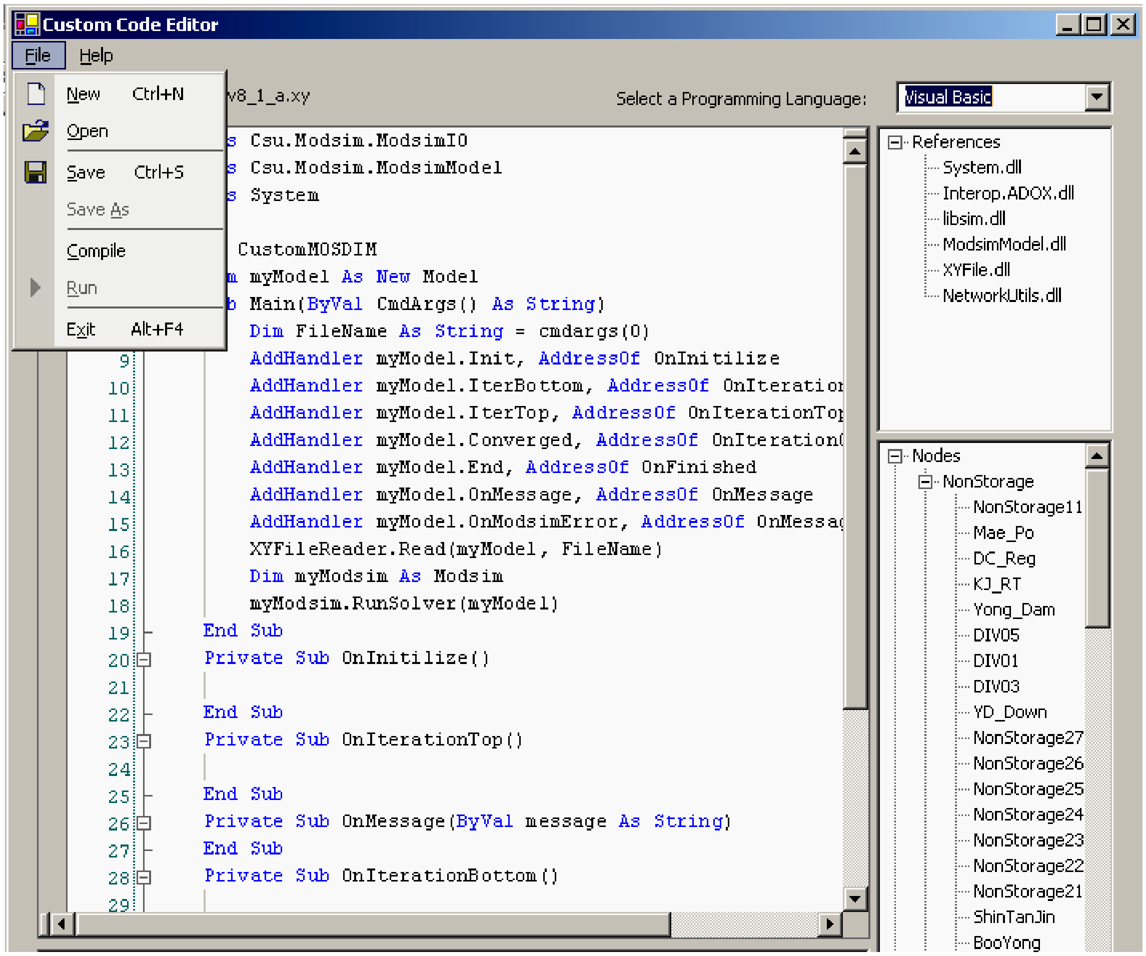


Once the system network has been created and the database populated, MODSIM can be executed from the interface under **MODSIM** > **Run MODSIM**.



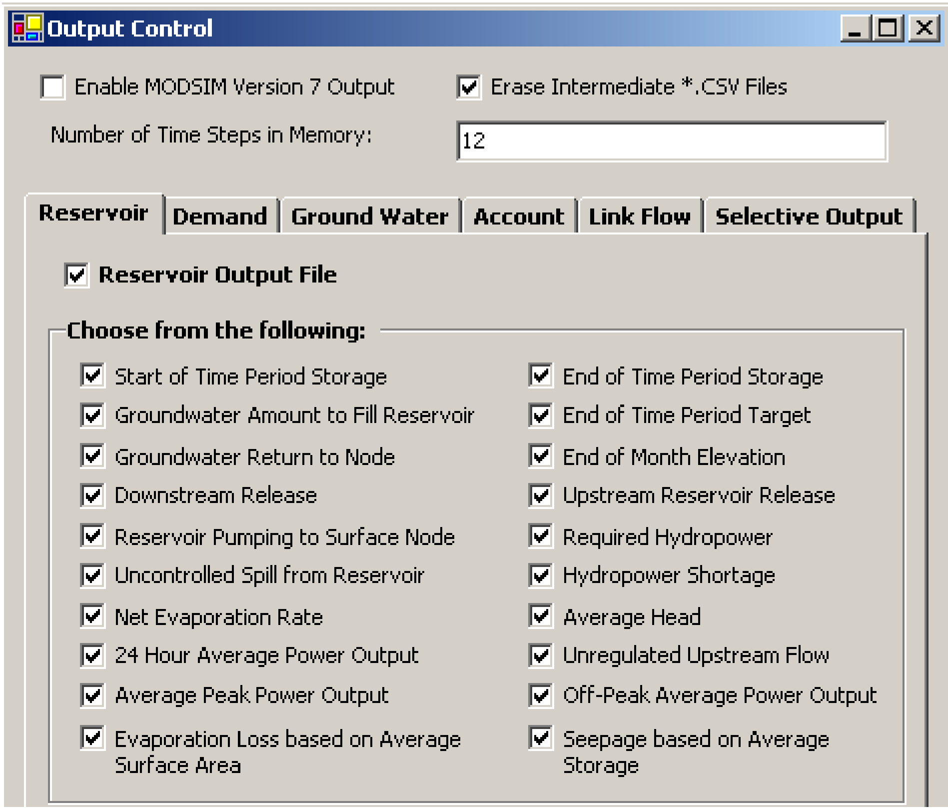
A number of useful **Extensions** are included with MODSIM: **Storage Rights**, **Back-Routing**, **Water Rights**, and **Last-Fill Extensions**.





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. Customized versions of MODSIM can be compiled and executed from the interface. A convenient template is provided in the **Custom Code Editor** for guiding users in the preparation of customized code. The customized code can interface with MODSIM at any desired strategic locations, including data input, execution at the beginning of any time step, processing at intermediate iterations, and model output. Users are provided direct access to all of *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. Details on use of the **Custom Code Editor**, along with several examples of custom code development, can be found in Tutorial C in the set of Tutorials associated with this User Manual.

Output Control provides an extensive variety of graphical and text output options for any combinations of network objects and output data types. In the production of output results, the user can specify the number of time steps held in memory. Retaining output results over several time steps in main memory generally results in faster execution speed, but also requires larger SDRAM memory.



C. Network Flow Optimization

Links and nodes in MODSIM are not confined to representing *physical* and hydrologic features of a river basin system, but are also used to symbolize *artificial* and conceptual elements for modeling complex administrative and legal mechanisms governing water allocation. In addition to the links and nodes defined by users, several artificial nodes and links are automatically created by MODSIM, as shown in Fig. 4. These artificial nodes and links are essential to insuring mass balance is satisfied throughout the network. It should be noted that MODSIM users are only responsible for defining the physical flow network. All artificial nodes and links are added automatically by the model.

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

$$\text{minimize} \quad \sum_{k \in A} c_k \, q_k \tag{1}$$

subject to:

$$\sum_{k \in O_i} q_k - \sum_{j \in I_i} q_j = b_{it}(\mathbf{q}) \quad \text{for all nodes } i \in N \tag{2}$$

$$l_{kt}(\mathbf{q}) \le q_k \le u_{kt}(\mathbf{q}) \quad \text{for all links } k \in A \tag{3}$$

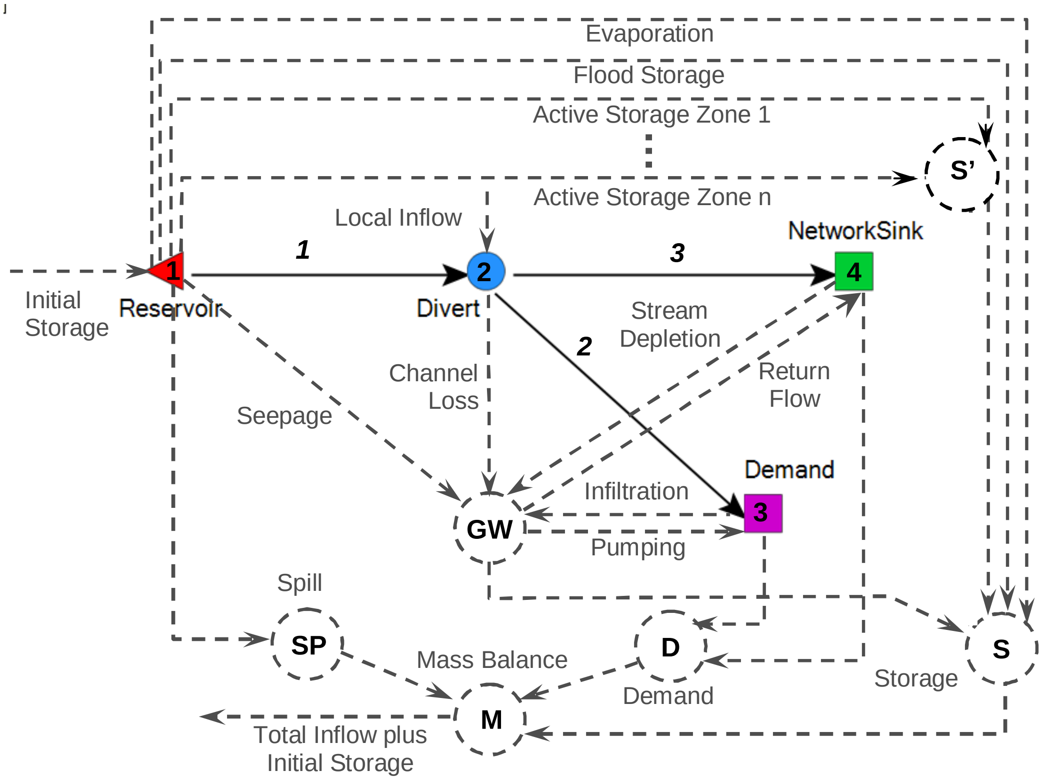


Fig. 4. Illustration of MODSIM network structure with artificial nodes and links.

where A is the set of all arcs or links in the network; N is the set of all nodes; O_i is the set of all links originating at node i (i.e., outflow links); I_i is the set of all links terminating at node i (i.e., inflow links); b_{it} is the (positive) gain or (negative) loss at node i at time t ; q_k is the flow rate in link k ; c_k are costs, weighting factors, or water right priorities per unit flow rate in link k ; and l_{kt} and u_{kt} are specified lower and upper bounds, respectively, on flow in link k at time t. Note that parameters b_{it} , l_{kt} , u_{kt} are defined as functions of the flow vector $\mathbf{q}$ in the network. These nonlinearities are due to flow dependent calculation of evaporation (based on flow in the carryover storage artificial arcs shown in Fig. 4), groundwater return flows, channel losses, and instream flow requirements, and are primarily associated with the artificial arcs.

A *successive approximations* solution procedure is adopted for solution of Eqs. 1-3 whereby an initial set of flows $\mathbf{q}$ are assumed, resulting in initial estimates of the flow-dependent parameters b_{it}, l_{kt} , u_{kt} . Eqs. 1-3 are then solved with the highly efficient 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. Technical details on the RELAX algorithm can be found in Appendix A to this report. Flows $\mathbf{q}$ produced from this solution then serve to update estimates of parameters b_{it} , l_{kt} , u_{kt} , and the network flow optimization repeats until convergence. Optimization is primarily conducted as a means of accurately *simulating* the allocation of water resources in accordance with operational priorities based on system objectives, operational experience, water rights, and other ranking mechanisms, including economic factors.

Network topology and object characteristics are defined by sets N, A, I_i, and O_i and arc parameters $[l_{kt}, u_{kt}, c_k]$ for each arc or link k, for each period t. Since solution of Eqs. 1-3 is executed period by period, rather than as a fully dynamic optimization, flows in carry-over storage arcs (Fig. 4) become initial storage levels for the next period optimization. Fig. 5 summarizes the functionality and data requirements of each MODSIM object.

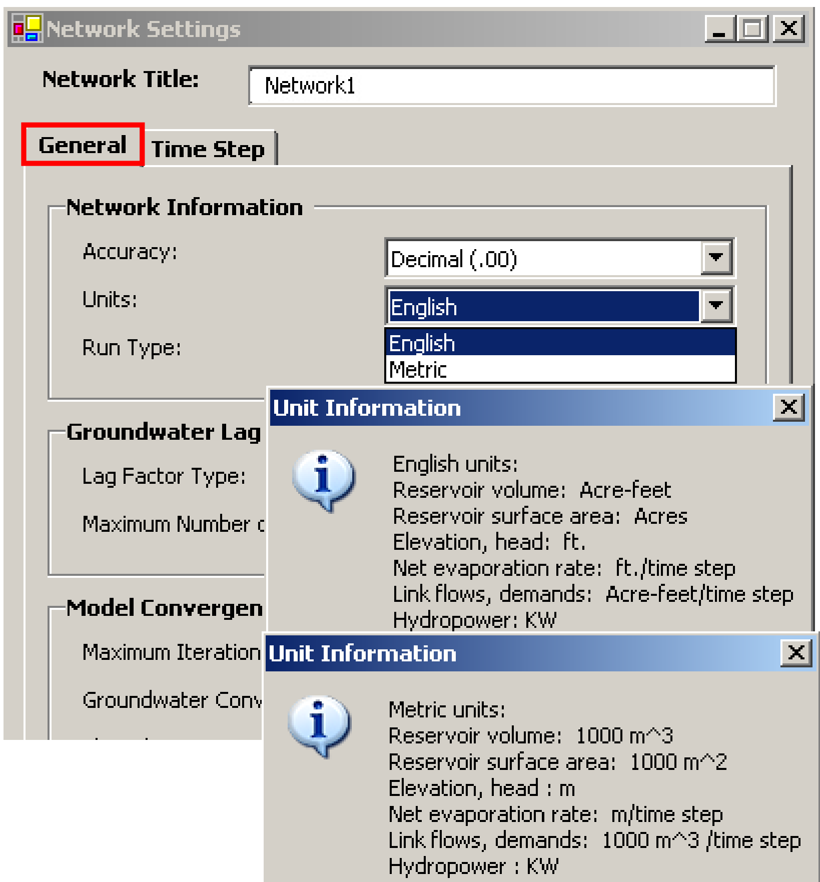
Icon	Functionality	Data Requirements
Reservoir [Operations]	▪ Main-stem and offstream reservoir operations ▪ Flood control, conservation pools; dead storage ▪ Zones for storage balancing in multi-reservoir systems	▪ Elevation-area-capacity tables ▪ Maximum, minimum, initial storage ▪ Reservoir storage guidecurves ▪ Reservoir balance tables ▪ Hydraulic outlet capacity tables ▪ Net evaporation loss; seepage ▪ Inflow forecasts (if available)
Reservoir [Hydropower]	▪ High-head hydropower ▪ Run-of-river hydropower [0 storage] ▪ On-peak, secondary and firm energy ▪ Pumped storage	▪ Nonlinear efficiency tables as functions of head and discharge ▪ Tailwater-discharge tables ▪ Powerplant capacity ▪ Load factors for pumped storage
StorageRight Reservoir	▪ Storage right accounts ▪ Storage ownership maintenance ▪ Water banking and service contracts	▪ Storage right users ▪ Group ownerships
NonStorage	▪ Watershed runoff ▪ Tributary inflow ▪ Flow confluence and diversion ▪ Groundwater return flows ▪ Stream depletion from pumping	▪ Imported inflow time series data ▪ Execution of external rainfall-runoff models through custom code
Demand	▪ Consumptive demand ▪ Groundwater pumping ▪ Stream-aquifer modeling with Glover model or USGS stream depletion factor (sdf) method	▪ Import of demand time series data ▪ External consumptive use models ▪ Demands/priorities conditioned on hydrologic state ▪ Water use efficiency (time variable) ▪ Aquifer parameters; pumping capacity
Flowthru	▪ Instream flow requirements environmental, ecological or navigation purposes ▪ Nonconsumptive demands ▪ Gaging station for model calibration	▪ Time series of instream flow requirements ▪ Flow-through demands and priorities vary with hydrologic conditions ▪ Measured flow data for calibration
NetworkSink	▪ River basin outlet (multiple outlets for several basins allowed)	
Link	▪ Channel losses ▪ Maximum and Minimum Flow	▪ Time series of maximum capacities ▪ Link costs and benefits
MultiLink	▪ Represent nonlinear discharge-channel loss functions ▪ Nonlinear cost-discharge functions ▪ Multiple water sources and rights	▪ Time series of maximum capacities ▪ Link costs and benefits
Routing Link	▪ Streamflow and channel routing	▪ Muskingum method coefficients ▪ User defined lag coefficients

Fig. 5. MODSIM functionality and features.

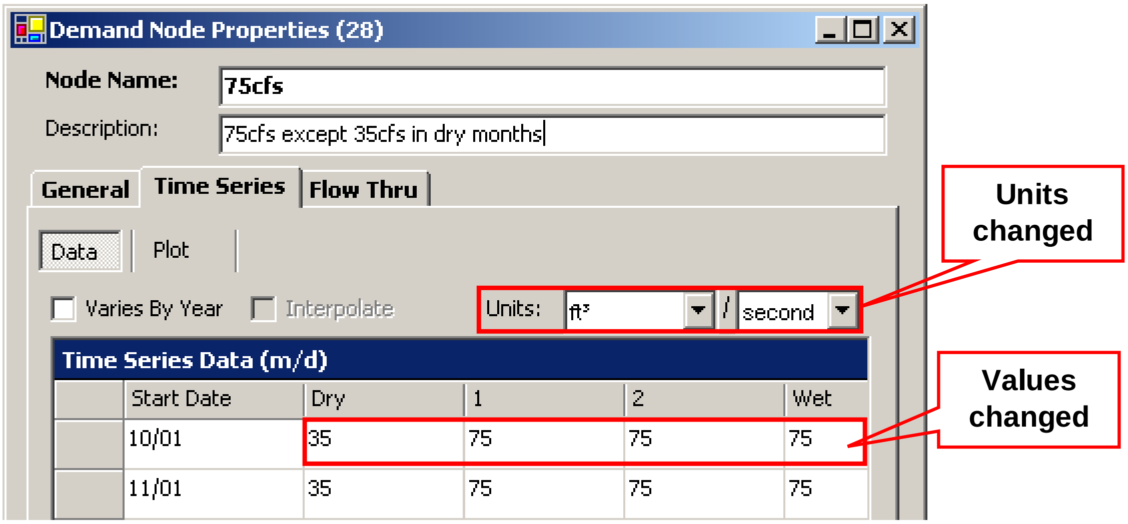
IV. GENERAL SETTINGS FOR MODSIM NETWORKS

A. Accuracy and Units

Network Settings > **General** under **MODSIM** on the main menu bar allows users to specify a number of options. The desired accuracy for data input and flow results can be either integer accuracy or 2-place decimal accuracy. Users can select either English or metric units, with the default units used for storage, flow, head, net evaporation rates and hydropower specified. However, users may input data in any desired units in the node and link properties forms, and MODSIM will automatically convert the data to the default units.

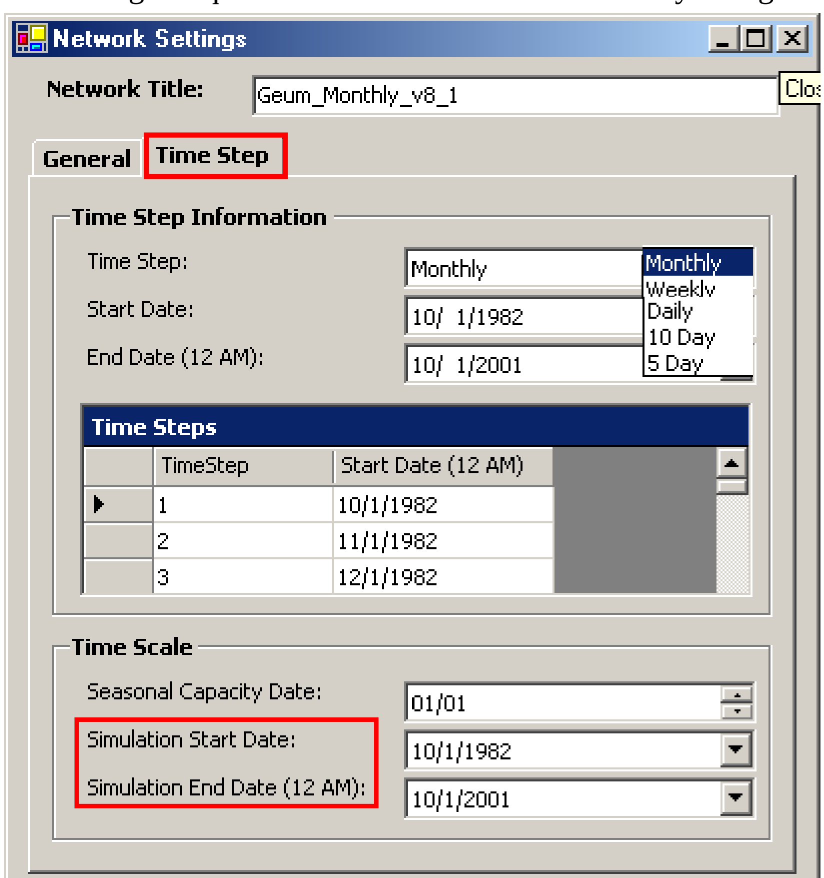


Units can be changed directly in the Node or Link Properties forms. For example, consider again the **Demand Node Properties** form for the flow-through demand *75cfs* in the example *Prineville* network. It is desired to change the original units of ac-ft/month to average cfs (ft^3/sec) over each time step. The units are easily changed to ft^3/second in the dropdown lists in the **Units** field of the form.



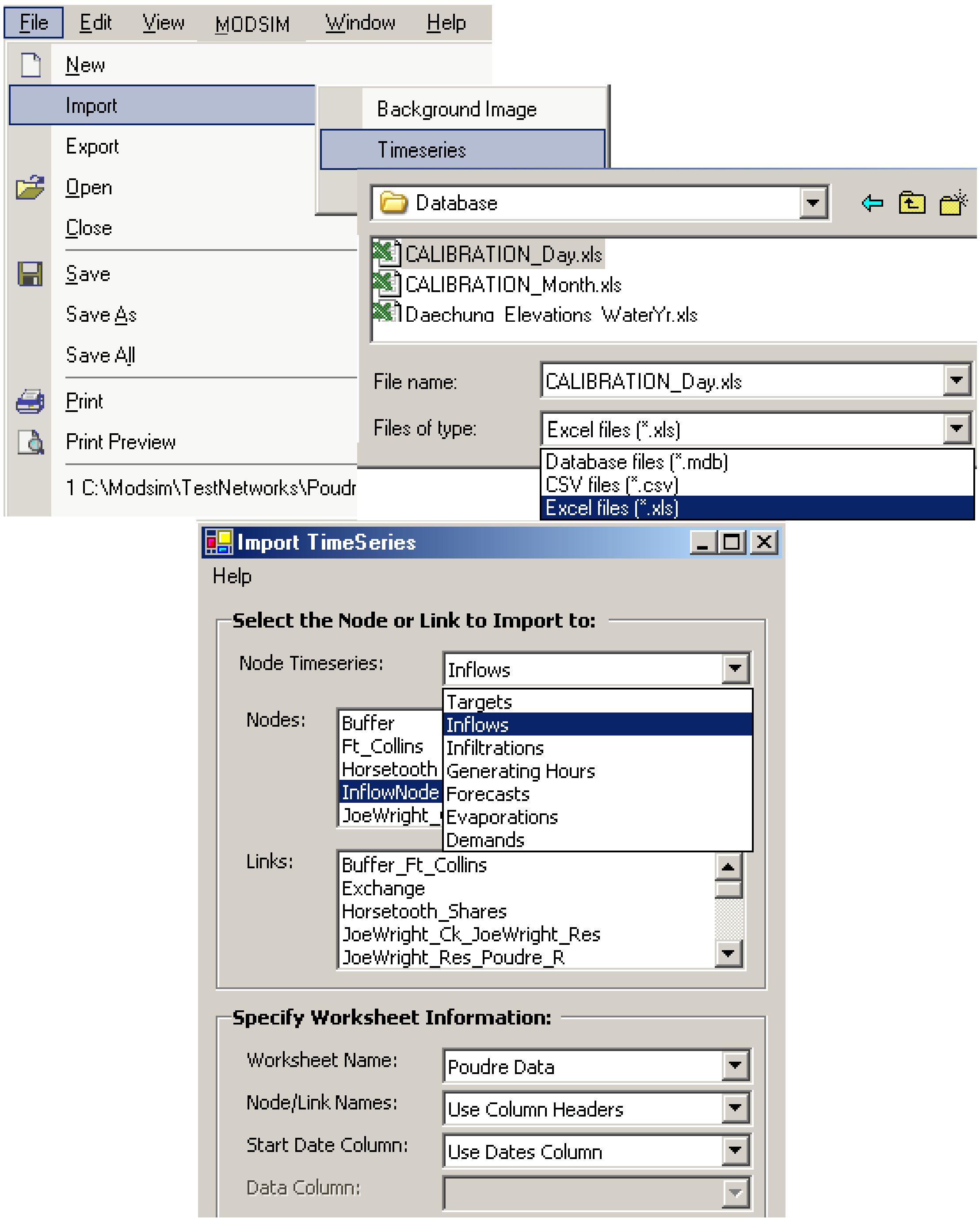
B. Time Steps and Scale

MODSIM > **Network Settings** > **Time Step** allows *monthly*, *weekly*, or *daily* simulation time steps to be specified, as well as *10-day* and *5-day* time steps for certain international applications. *Start Date* and *End Date* for time series data entered into MODSIM must be the same for all data including inflows, demands, reservoir storage targets, etc. However, a MODSIM simulation run can start and end at any intermediate dates, as specified in the **Time Scale** field of the form. This is useful, for example, for critical period studies on drought sequences within the entire historical hydrologic data set.



C. Import of Time Series Data

The MODSIM GUI includes powerful tools for automatically importing time series data from MS Access (*.dbf), MS Excel (*.xls), and comma-separated ASCII files (*.csv) into node and link objects, including unregulated inflows, demands, target storage levels, and link capacities. If the database column headers correspond to the exact names (case sensitive) of the MODSIM nodes and links, then the **Import Time Series** tool automatically loads the appropriate data into those objects.



D. Background Images

MODSIM provides tools for importing terrain images and feature maps of the study area for configuring network nodes and links corresponding to spatial locations of system elements. Images can be created from GIS layers, downloaded from Internet map providers, or obtained from sources such as Google Earth for high resolution aerial and satellite imagery and feature data sets for any location on earth. Map images can be enlarged or reduced in the *Network Editor Window*. Although several map images can be loaded, only the top layer is visible in the Window.

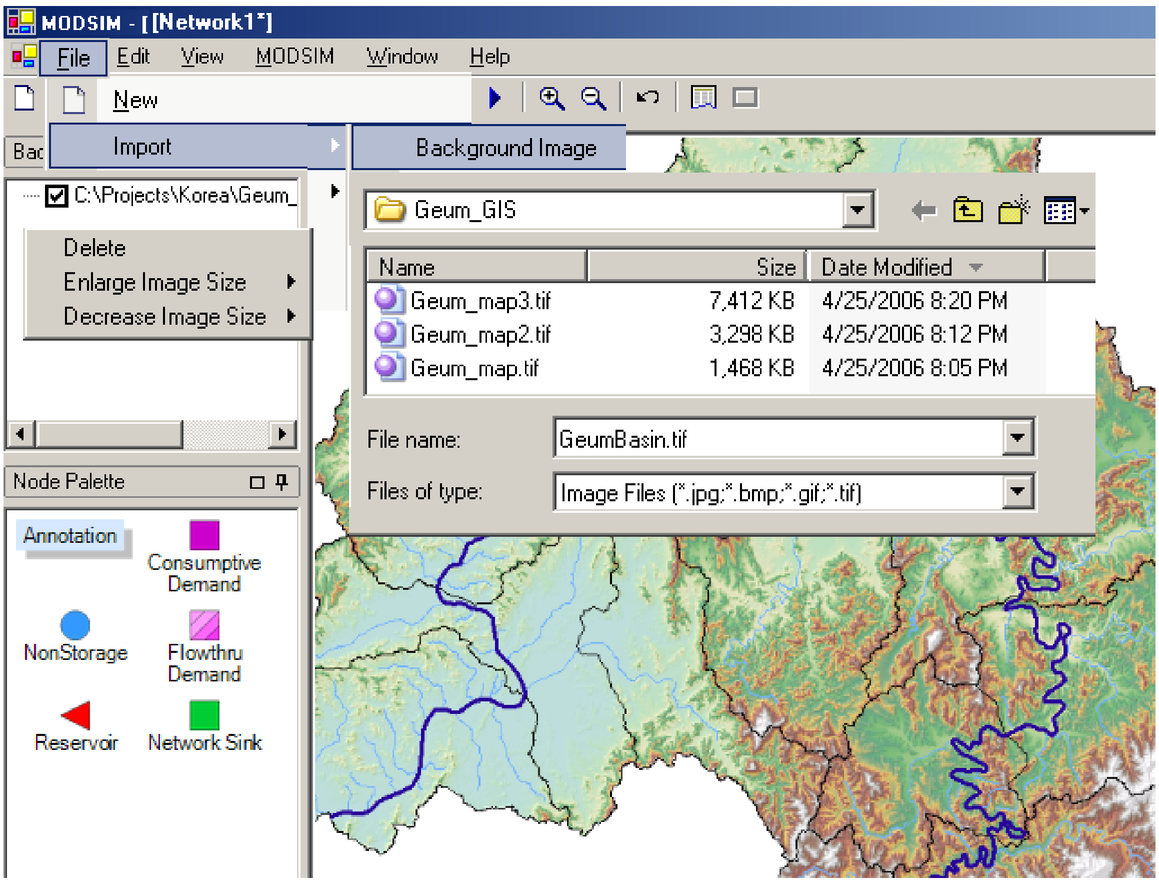


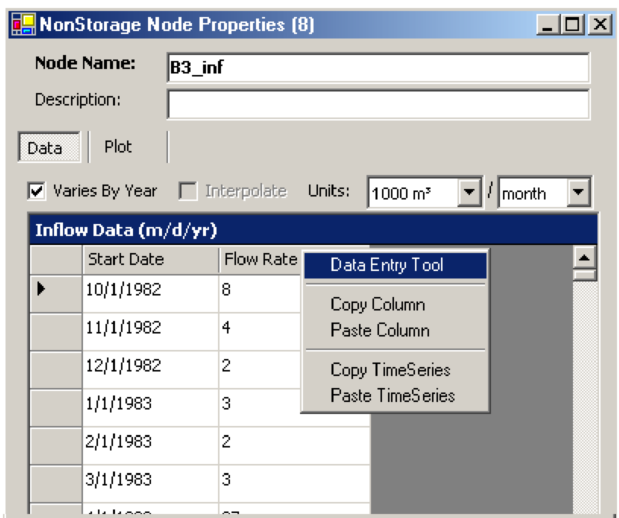
Fig. 5. Import of background images into the MODSIM display.

V. SURFACE WATER MODELING COMPONENTS

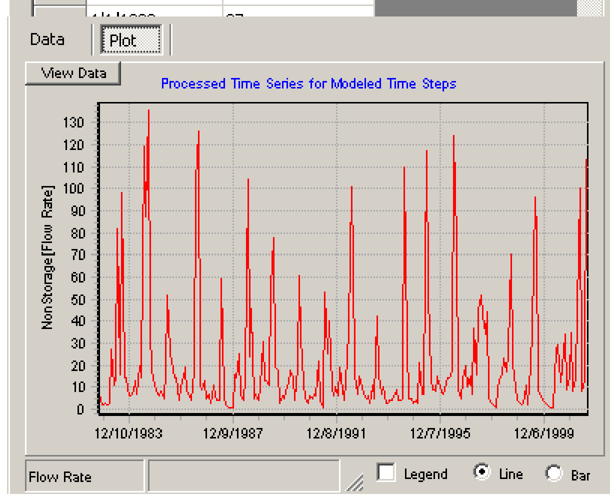
A. Unregulated Inflows

Native or unregulated hydrologic inflows are input into MODSIM from measured flow data, watershed runoff models, forecasts, drought scenarios, or stochastic generation of streamflows. Unregulated inflows are assigned as right-hand-side constants in Eq. 2 for nonstorage nodes serving as inflow nodes. Unlike other river basin models, the inflows supplied to MODSIM are unregulated, incremental, or localized inflow gains to a river reach. River basin models such as TAMUWRAP (Wurbs and Walls, 1989) and STATEMOD (State of Colorado, 1999) require the user to develop virgin or undeveloped flow conditions in the basin prior to application of the model, which are often difficult to synthesize. Larson (2003) applied the SAMS software package (Salas, et al., 2002) for stochastic generation of streamflow gains to the Snake River basin for a MODSIM application, and Labadie, et al. (2004) applied SAMS to stochastic generation of streamflows for application of MODSIM to the Geum River Basin, Korea.

Double-clicking any **NonStorage Node** in the *Network Editor Window* displays the **NonStorage Properties** form for entry of unregulated inflows. Inflow data can be entered automatically using the **Import Time Series Tool**, or manually for short time series data. *Right-button mouse click* on the *Flow Rate* column heading produces a context menu for copying data from a spreadsheet, database, or ASCII text file into the Windows Clipboard to be pasted into this form. Large database files may be automatically loaded into MODSIM using custom code written in one of the MS.NET languages. Unchecking the **Varies By Year** box allows entry of seasonal data that repeat every year for the length of the simulation.



Clicking the **Plot** button in the **NonStorage Node Properties** form generates a graph of the time-series data entered in the form. This is useful as a visual means of scanning the data for obvious outliers and inconsistent data. Holding the left-button mouse and dragging a box clockwise over the graph zooms to the selected portion. Dragging a box counter-clockwise through the origin returns the graph to its original resolution.

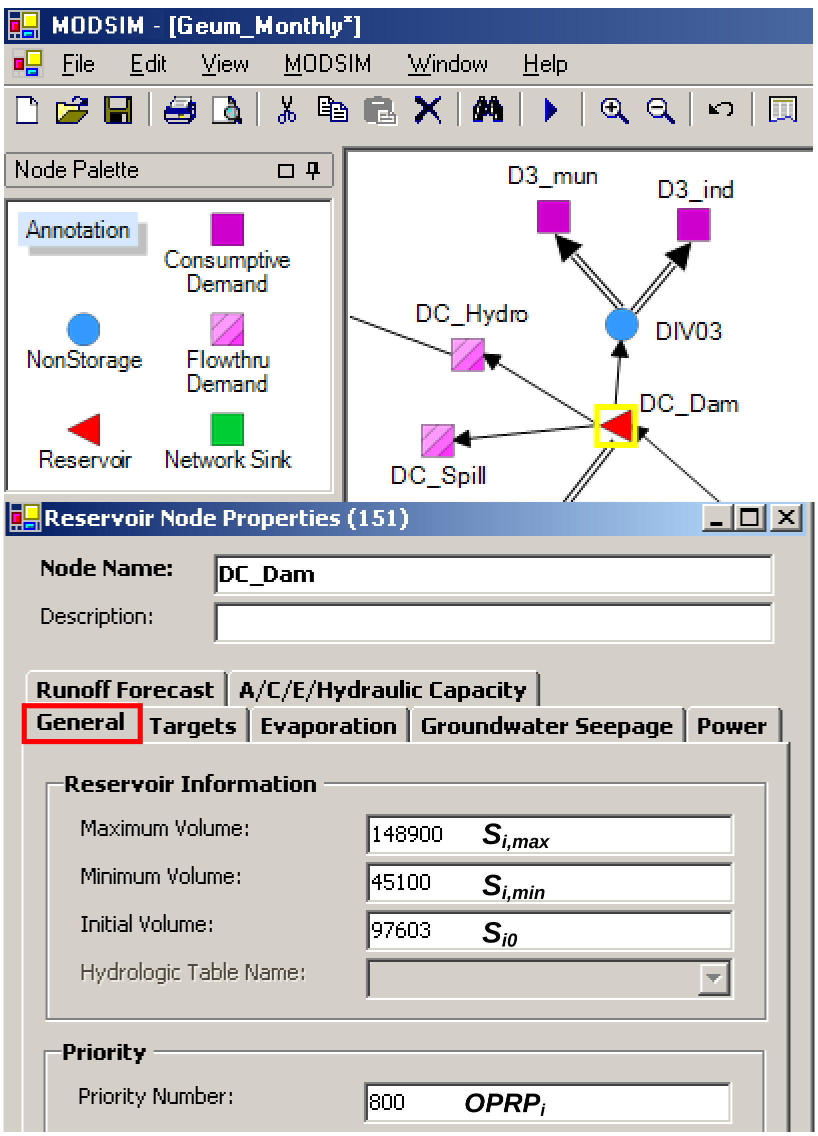


B. Reservoir Operations

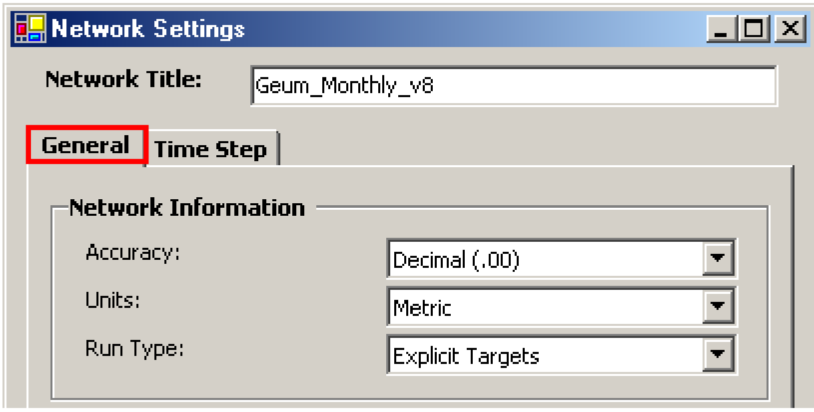
Reservoir Information and Priorities. Reservoir *Maximum Volume* $S_{i,max}$, *Minimum Volume* $S_{i,min}$, *Initial Volume* S_{i0} , and reservoir *Priority Number* are entered into the **General** tab of the **Reservoir Node Properties** form, where the artificial carryover storage link cost is:

$$c_i = -\left(50000 - 10 \cdot OPRP_i\right) \tag{4}$$

where $OPRP_i$ is an integer priority ranking from 1 to 5000, with lower numbers indicating a higher ranking, resulting in a negative cost. Notice that minimization of negative costs in Eq. 1 is equivalent to maximizing flows to the higher ranked water uses. Rather than their absolute values, it is the relative order or ranking of the negative costs that determines how MODSIM allocates network flows.



Reservoir Storage Zones. Specification of **Run Type** as *Explicit Targets* under **MODSIM > Network Settings > General** allows input of **Reservoir Target Storage** levels T_{it} for reservoir *i* for each time step *t* under the **Targets** tab of the **Reservoir Node Properties** form. The use of *Explicit Targets* is often valuable for calibrating MODSIM by specifying target storage levels as measured historical data and then adjusting various parameters in MODSIM to match available stream gage records.



The **Reservoir Target Storage** levels represent the top of the active or conservation storage pool of the reservoir. MODSIM allows the conservation pool to be divided into several operational zones which serve to improve regulation of storage levels in multi-reservoir systems. For example, without the use of storage zones, network solutions may result in some reservoirs remaining full and others being emptied, depending on the priorities assigned to the maintaining the storage targets. Fig. 7 shows the artificial carryover storage links for each storage zone originating at each reservoir and accumulating at artificial carryover storage node **S**. The *link* or *arc parameters* are displayed in Fig. 6, where (negative) costs for the storage zone arcs are incremented from the negative cost associated with maintaining the active storage target in the reservoir.

Bounds on the zone carryover storage links represent the incremental storage in each zone as defined by the user in the MODSIM GUI, where α_i is the fraction of either maximum capacity or target storage defining zone layer *i*, and Δc_i is the corresponding

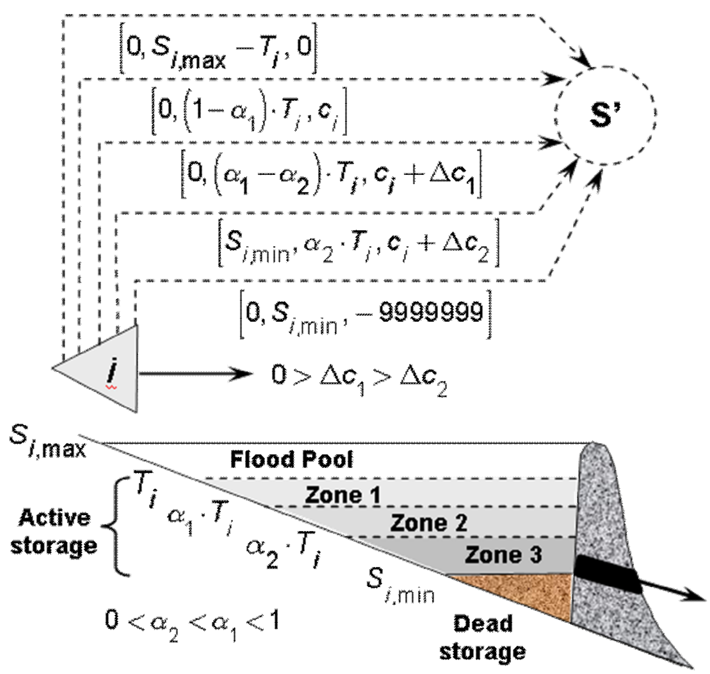
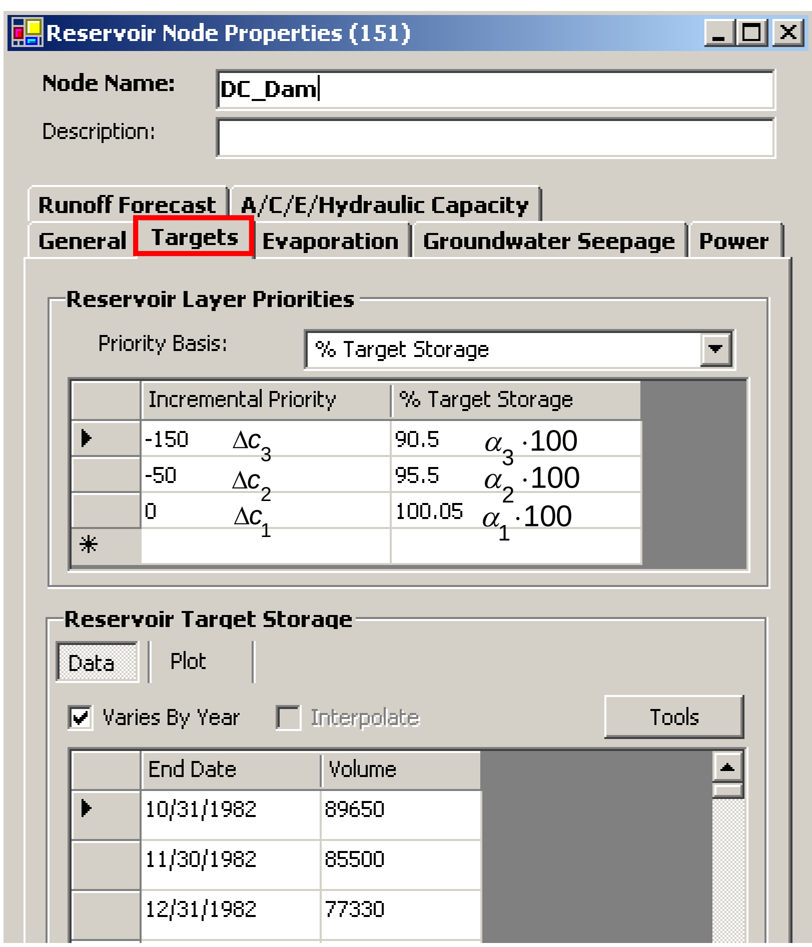


Fig. 7. Link parameters for zone carryover storage arcs.

incremental (negative cost) for zone *i*, which are entered as **Reservoir Layer Priorities** in the **Reservoir Node Properties** form under the **Targets** tab. To achieve relatively balanced storage among several reservoirs in a basin, each reservoir should have the same $OPRP_i$ priority and similar incremental costs Δc_i .

Flood Operations. Although MODSIM is not primarily designed for flood operation studies, flood pool zones are defined above the target storage levels in reservoirs, as shown in Fig. 7. These target storage levels can vary seasonally for securing increased space during the flood season. As seen in Fig. 7, the flood carryover storage link is assigned a zero cost in MODSIM. In conjunction with the flood space, the final terminal node in a river basin should be a **Network Sink Node,** as shown in Fig. 8. The **Network Sink Node** is assigned a default priority number of 4999, resulting in a small negative cost of -10 on the artificial demand link conveying flows out of the basin (Eq. 4). A high demand is assigned to the **Network Sink Node**, assuring feasible network solutions under high flow conditions. Since the artificial flood zone carryover arcs are assigned a zero cost, any temporary storage in the flood zone is released downstream as soon as sufficient conveyance capacity is available. In addition, high cost artificial spill links shown in Fig. 4 convey excess flows out of the basin only if available flood space is filled and downstream conveyance channels are at maximum capacity. If it is desired to retain excess spill flows in the basin, parallel, high cost links can be created downstream to represent overbank flooding.



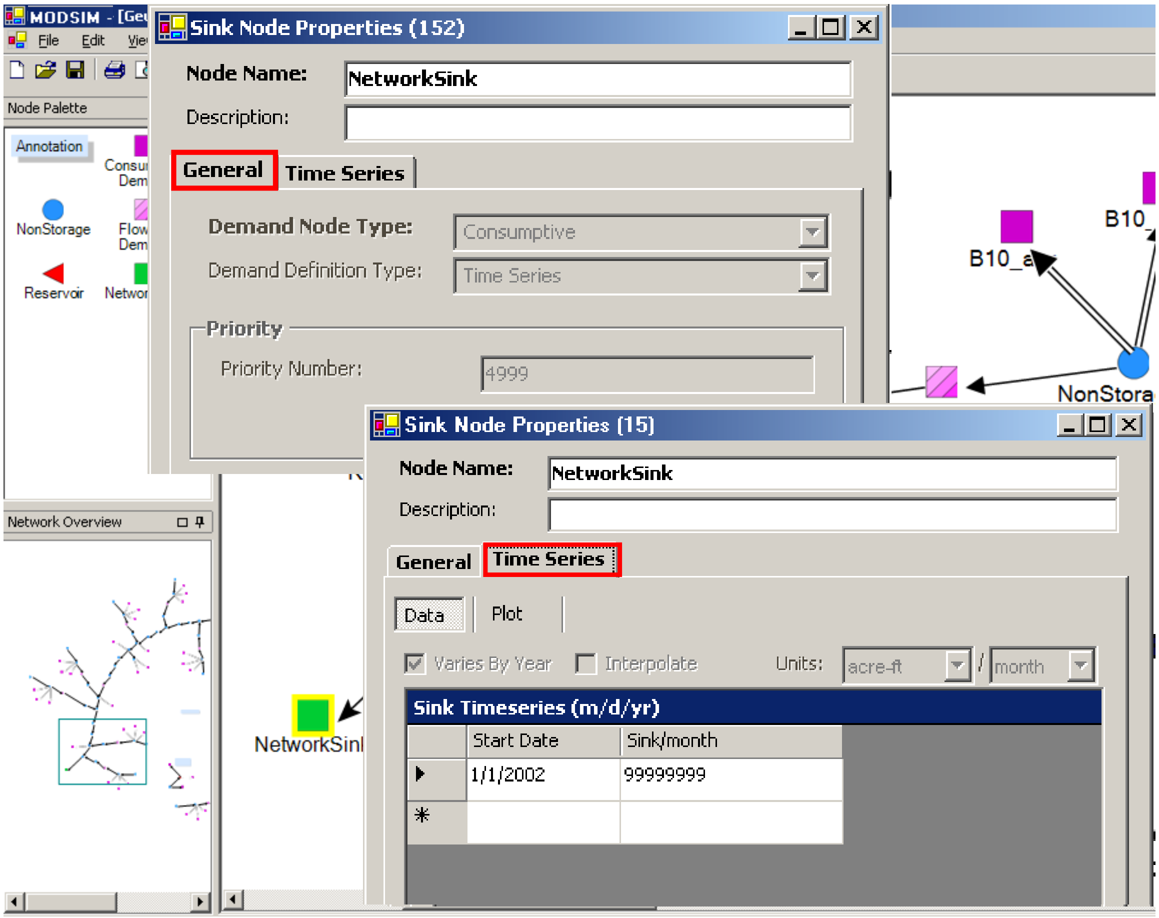
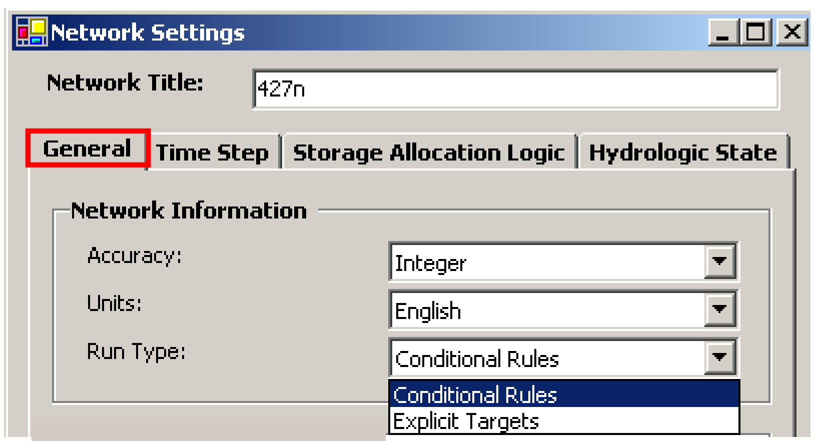


Fig. 8. Network sink node located at basin outlet.



Conditional Operating Rules. Under the **General** tab of the **Network Settings** form, specification of **Run Type** as *Conditional Rules* allows target storage levels to be conditioned on user defined *Hydrologic State* information at the current time step. The use of Hydrologic State information is valuable for management simulation runs of MODSIM after the completion of model calibration.

Hydrologic States. MODSIM computes Hydrologic States by considering current reservoir storage levels and current period forecasts to a certain user specified subset of reservoirs in the system that are indicative of hydrologic conditions in the basin. Several different Hydrologic State subset designations may be specified as needed. Associated with each of these states (which may be classified as average, dry, wet, etc.) is a corresponding set of reservoir operating rules with associated ranking priorities. These Hydrologic States are computed at the beginning of each period for the user selected reservoir subset through the following analysis:

$$R_{tm} = \sum_{i \in H_m} \left[S_{it} + F_{it} \right] \tag{5}$$

$$W_m = \sum_{i \in H_m} S_{i,\max} \tag{6}$$

where H_m is the set of node numbers of reservoirs in a specified subset defining Hydrologic State designation m; t is the current period of operation; F_{it} is a *Runoff Forecast* for reservoir i at period t; S_{it} is the beginning storage in reservoir i, period t; and $S_{i,max}$ is the storage capacity for reservoir i.

The ranges for each Hydrologic State designation are defined by user input *boundary factors* $\beta_{i\tau m}$ (i = 1,…,n-1) as fractions of total subsystem storage capacity for *seasonal* period τ (i.e., calendar month for monthly time steps in the simulation), where

$$0 \le \beta_{1\tau m} < \cdots < \beta_{i\tau m} < \cdots < \beta \tag{7}$$

Boundaries dividing the Hydrologic State ranges are then calculated as:

$$\begin{aligned} B_{i\tau m} &= \beta_{i\tau m} W_m \quad \text{for } i = 1, \ldots, n-1 \\ B_{n\tau m} &= W_m \end{aligned} \tag{8}$$

where n is the number of Hydrologic States in designation m; $B_{i\tau m}$ is the upper bound on Hydrologic State i for period τ.

As illustrated in Fig. 9, the n Hydrologic State ranges for seasonal period τ are defined as:

$$\begin{aligned} &\textbf{Dry:} && 0 \le R_{tm} \le B_{1\tau m} \\ & && \vdots \\ &\textbf{Medium:} && B_{i-1,\tau m} \le R_{tm} \le B_{i\tau m} \\ & && \vdots \\ &\textbf{Wet:} && B_{n-1,\tau m} \le R_{tm} \end{aligned}$$

where period t is assumed to be in calendar month τ and reservoir targets T_{it} are constant with these

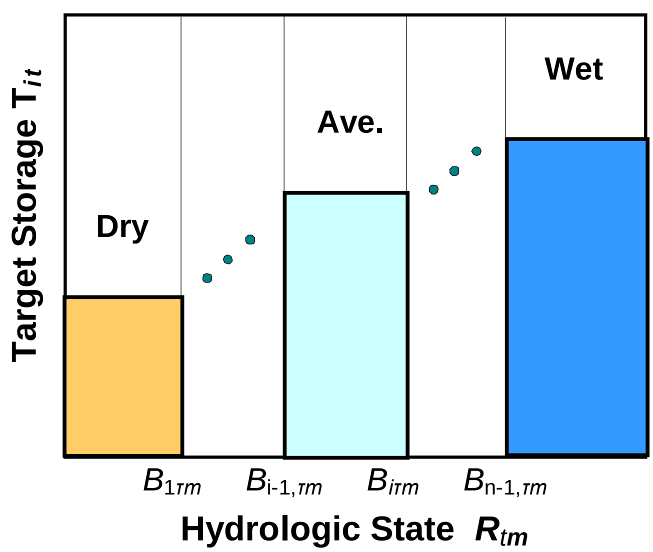
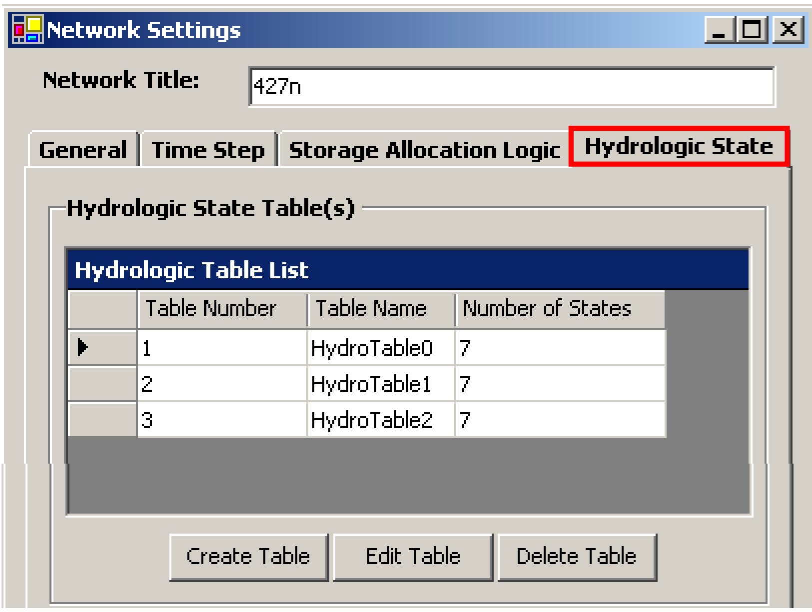


Fig. 9. Definition of Hydrologic States (assuming period t is calendar month τ.

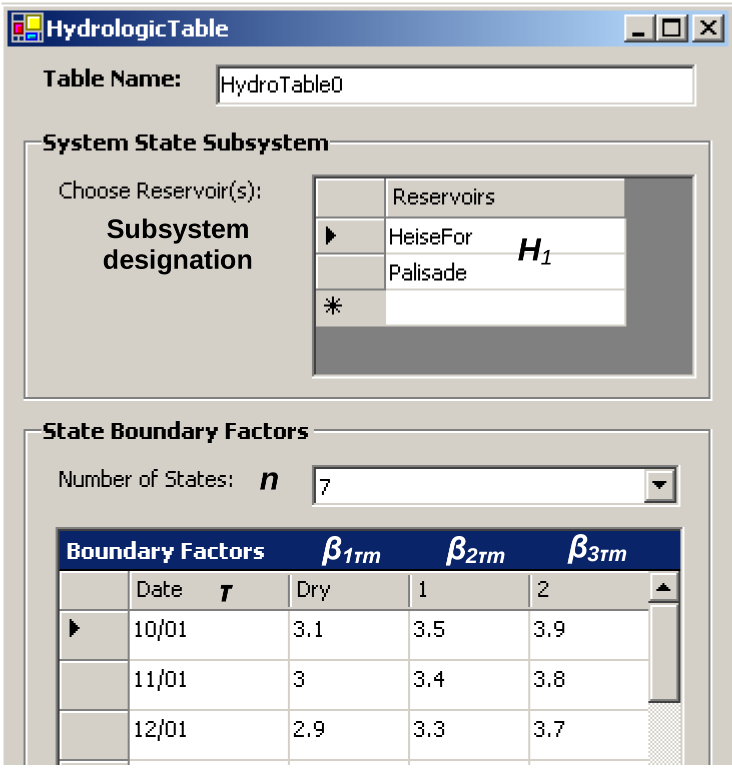
Hydrologic States. Conditional target storage levels can only vary within a computational cycle (i.e., one year for monthly time step simulation), although separate target storage levels can be specified for each Hydrologic State. MODSIM also allows differing priorities to be specified for any reservoir node corresponding to Hydrologic State conditions as calculated by the above procedure.

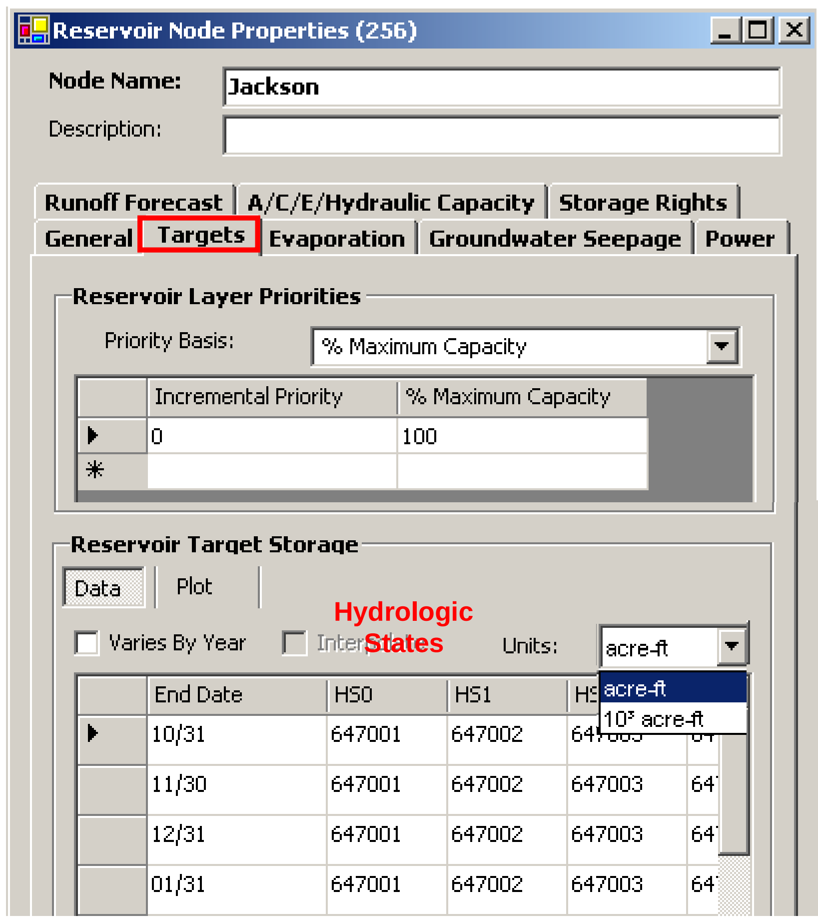
When *Conditional Rules* is selected as **Run Type** in the **Network Settings** form, a new **Hydrologic State** tab is displayed which lists existing **Hydrologic State Tables** that can be edited, bur also allows new tables to be created or existing tables deleted.



Clicking **Create Table** or **Edit Table** displays the **Hydrologic Table** form which allows designation of the Hydrologic State subsystem of reservoirs for conditional rules, as well as the boundary factors defining the range of each Hydrologic State. Boundary factors $\beta_{i\tau m}$ may be > 1 since reservoir operating targets are conditioned on total current storage *plus* total inflow *Forecasts* for reservoirs in the designated Hydrologic State subsystem. Since upper bounds $B_{i\tau m}$ are calculated by multiplying boundary factors $\beta_{i\tau m}$ by total storage capacity W_m, without inclusion of inflows, higher boundary factors account for the volume of unregulated inflows entering the reservoir.

Once Hydrologic State tables have been created, the desired **Hydrologic Table Name** is easily selected from the drop down list in the form activated by clicking the **General** tab in the **Reservoir Node Properties** form. Varying priorities can be specified for each Hydrologic State. The conditional reservoir operating targets can then be input for each Hydrologic State into the form activated by clicking the **Targets** *tab*. Again, these targets are only applied to seasonal time steps, i.e., the calendar months of each year. Since it may be preferred that some reservoirs in the system are operated with explicit rather than conditional target storage levels, clicking the *Varies By Year* checkbox allows input of explicit targets for each time period.


HydrologicTable
Table Name:
HydroTable0
System State Subsystem
Choose Reservoir(s):
Subsystem designation
Reservoirs
HeiseFor
Palisade
H1
State Boundary Factors
Number of States:
n
7
Boundary Factors
β1τm
β2τm
β3τm
Date
τ
Dry
1
2
10/01 3.1 3.5 3.9
11/01 3 3.4 3.8
12/01 2.9 3.3 3.7


Reservoir Node Properties (256)
Node Name:
Jackson
Description:
Runoff Forecast
A/C/E/Hydraulic Capacity
Storage Rights
General
Targets
Evaporation
Groundwater Seepage
Power
Reservoir Layer Priorities
Priority Basis:
% Maximum Capacity
Incremental Priority
% Maximum Capacity
0 100
Reservoir Target Storage
Data
Plot
Hydrologic States
Varies By Year
Units:
acre-ft
acre-ft
10³ acre-ft
End Date
HS0
HS1
10/31 647001 647002
11/30 647001 647002 647003
12/31 647001 647002 647003
01/31 647001 647002 647003

Runoff Forecasts. Runoff forecasts are entered into the **Reservoir Node Properties** form under the **Runoff Forecast** tab (Fig. 10). Since runoff forecasts are not provided as actual inflows, they can be represented as unitless measures such as the Palmer Drought Severity Index, or other subjective indices. If desired, runoff forecasts can be entered into reservoirs directly connected to the network. Again, these forecasts do not provide actual inflows to the reservoir, but can be used to include that reservoir in a Hydrologic State subsystem which, would also include the current storage in the reservoir.

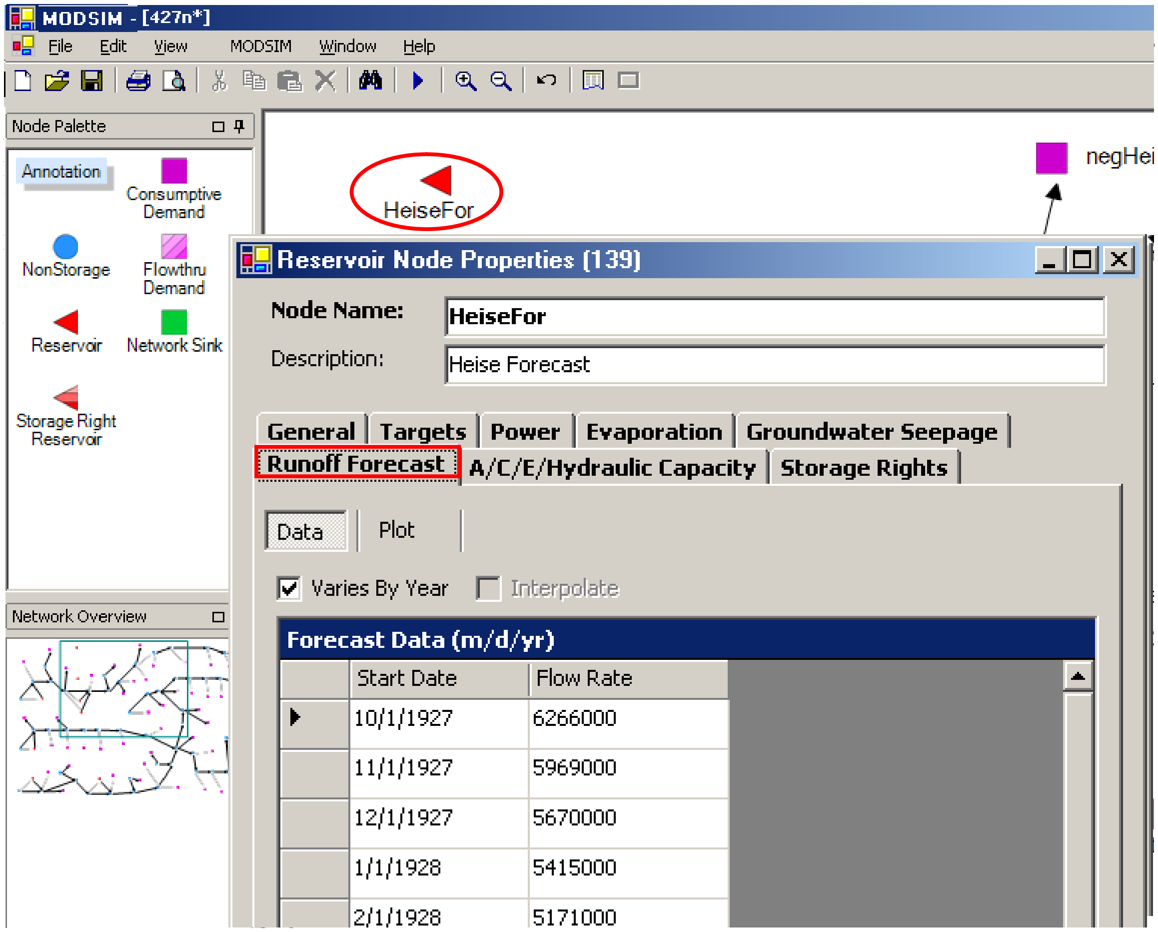
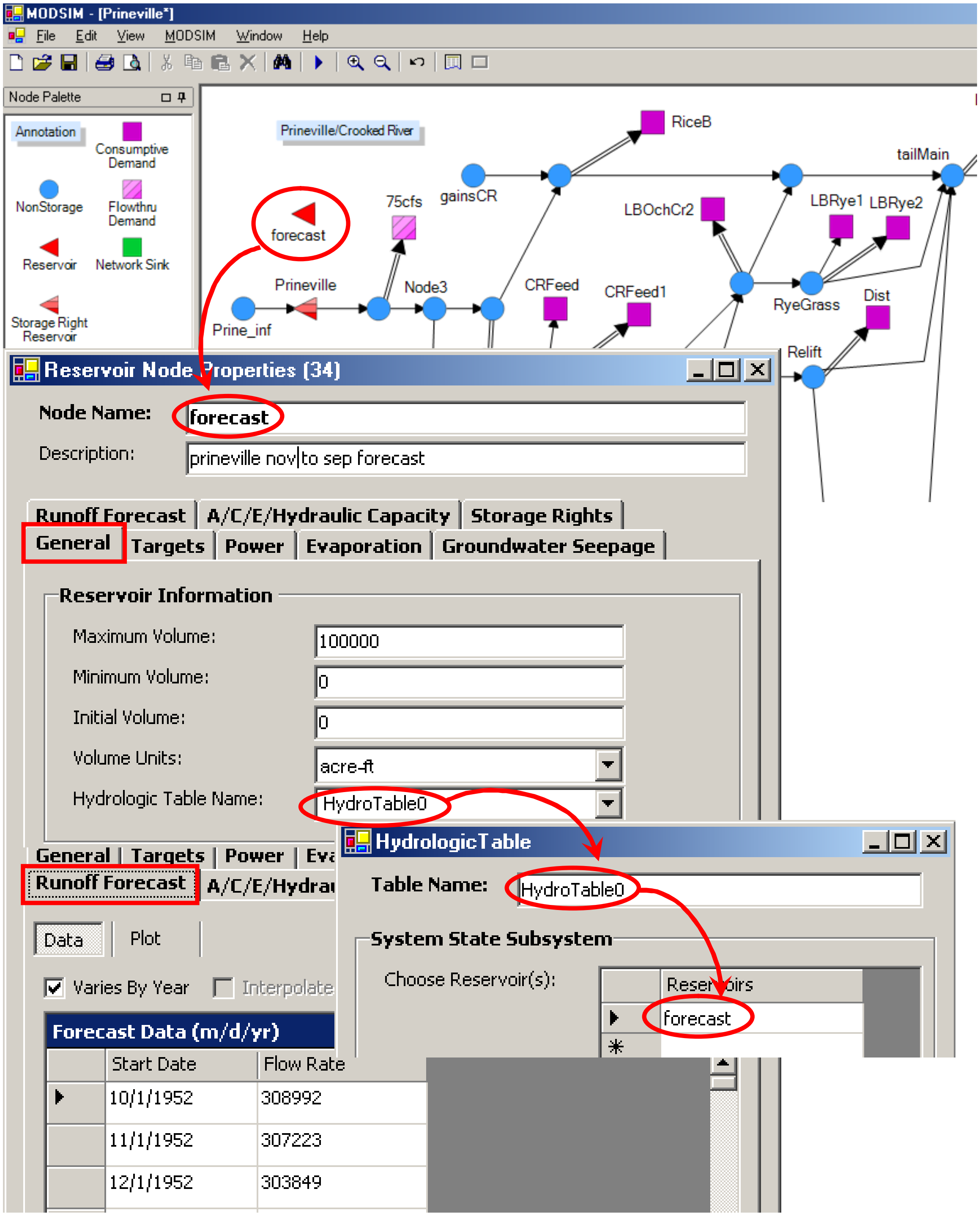


Fig. 10. Incorporation of runoff forecast information in *Reservoir Node Properties* form.

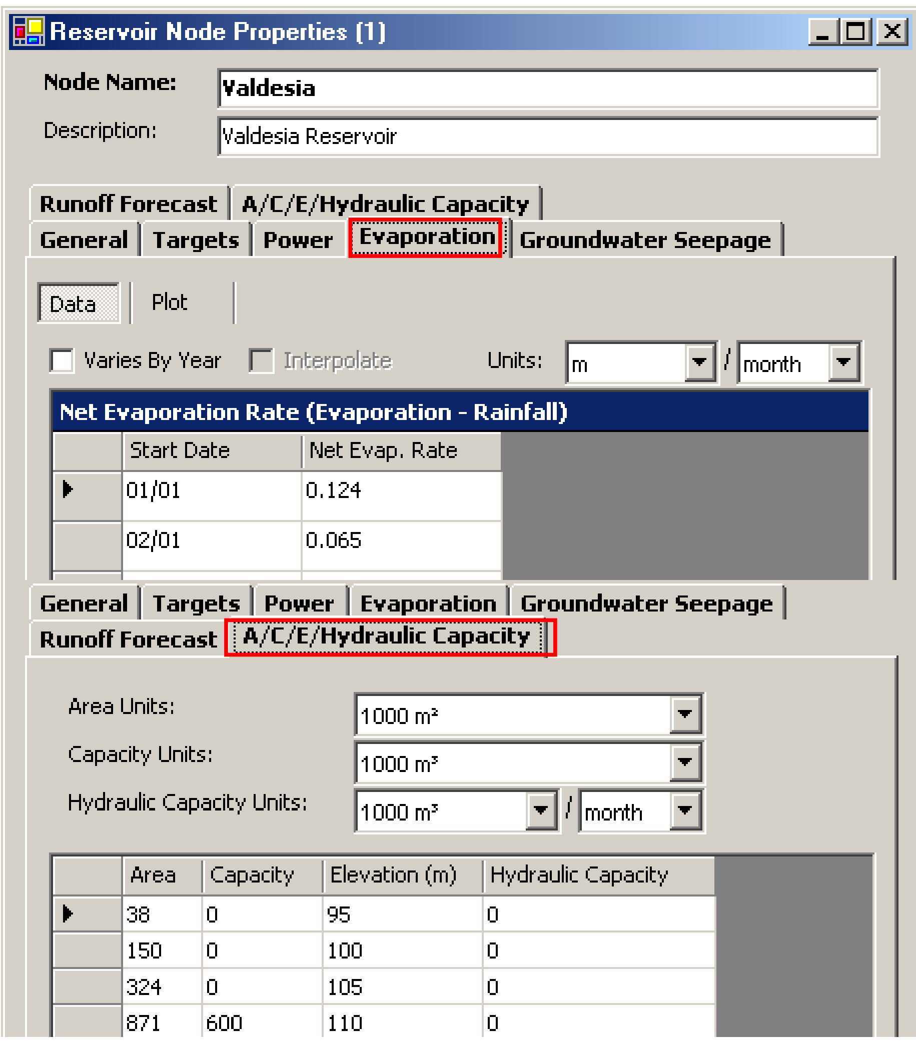


Seasonal runoff forecasts are entered into the form under the **Runoff Forecast** tab, allowing the dummy reservoir forecast to be included in the Hydrologic State subsystem designation of reservoirs used for developing conditional reservoir operating targets based on anticipated future inflow conditions, such as information obtained from snow pack surveys in the watershed. Data input to the **Runoff Forecast** form represents seasonal forecast information available at each time period of operation. Use of the dummy forecast reservoir is representative of the powerful **Watch Logic** capabilities incorporated in MODSIM, whereby operations at a particular location in a river basin can be influenced by *watching* flow and storage conditions in other portions of the basin.

Evaporation and Seepage Losses: Users enter *net* evaporation rates in the **Reservoir Node Properties** form, which are defined as evaporation rates minus rainfall rates. Negative entries signify that rainfall rates exceed evaporation rates for that time period. MODSIM accepts a variable number of elevation-area-storage-hydraulic outlet capacity data points for any reservoir, which are interpolated to calculate reservoir surface area corresponding to any current volume in the reservoir. Evaporation loss is calculated in MODSIM as a function of average surface area in a reservoir over the current period.

$$EV_{it} = ev_{it} \cdot 0.5 \cdot \left[A_i(S_{it}) + A_i(S_{i,t+1}) \right] \tag{8}$$

where ev_{it} is *net* evaporation rate (i.e., evaporation rate less rainfall rate) for reservoir *i* (e.g., m/month) for the current period *t* ; $A_i(S_{it})$ is the interpolated calculation of surface area from the *elevation-capacity-elevation-hydraulic outlet capacity* (**A/C/E/Hydraulic Capacity**) table for reservoir *i*, and S_{it} is storage at the beginning of the current period. Since average surface area in a reservoir is unknown until calculations are completed for the current period, an iterative process is required for accurate calculation of net

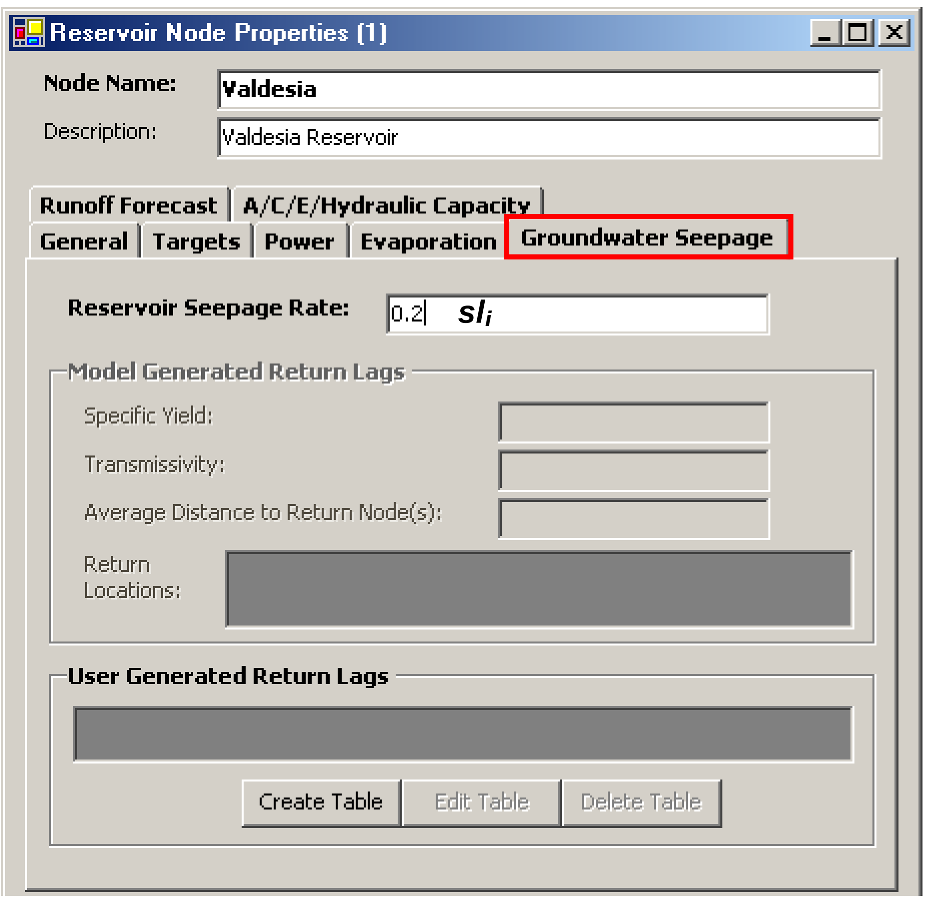


evaporation loss whereby net evaporation loss EV_{it} is initially calculated using surface area based on the reservoir beginning storage volume. With calculation of the ending storage volume for that period $S_{i,t+1}$ (or beginning storage volume for the next period), an updated estimate of net evaporation loss EV_{it} is calculated based on $A_i(S_{i,t+1})$, a new network solution is obtained based on the updated evaporation loss, and the process is repeated until the net evaporation loss calculations converge.

Seepage losses from reservoirs are calculated in a similar iterative process, except that seepage is assumed to be a function of average volume in the reservoir over the current period and the seepage loss rate is assumed to be constant:

$$SL_{it} = sl_i \cdot 0.5 \cdot [S_{it} + S_{i,t+1}] \tag{9}$$

where sl_i is the seepage loss fraction for reservoir i and SL_{it} is total volume of seepage loss during period t. In contrast with evaporation losses, a portion of reservoir seepage may be contributed to downstream return flows, as discussed subsequently. The seepage loss fraction is entered in the form activated by the **Groundwater Seepage** tab in **Reservoir Node Properties**. Entry of aquifer parameters or return flow lag coefficients allows calculation of downstream return flows from reservoir seepage.

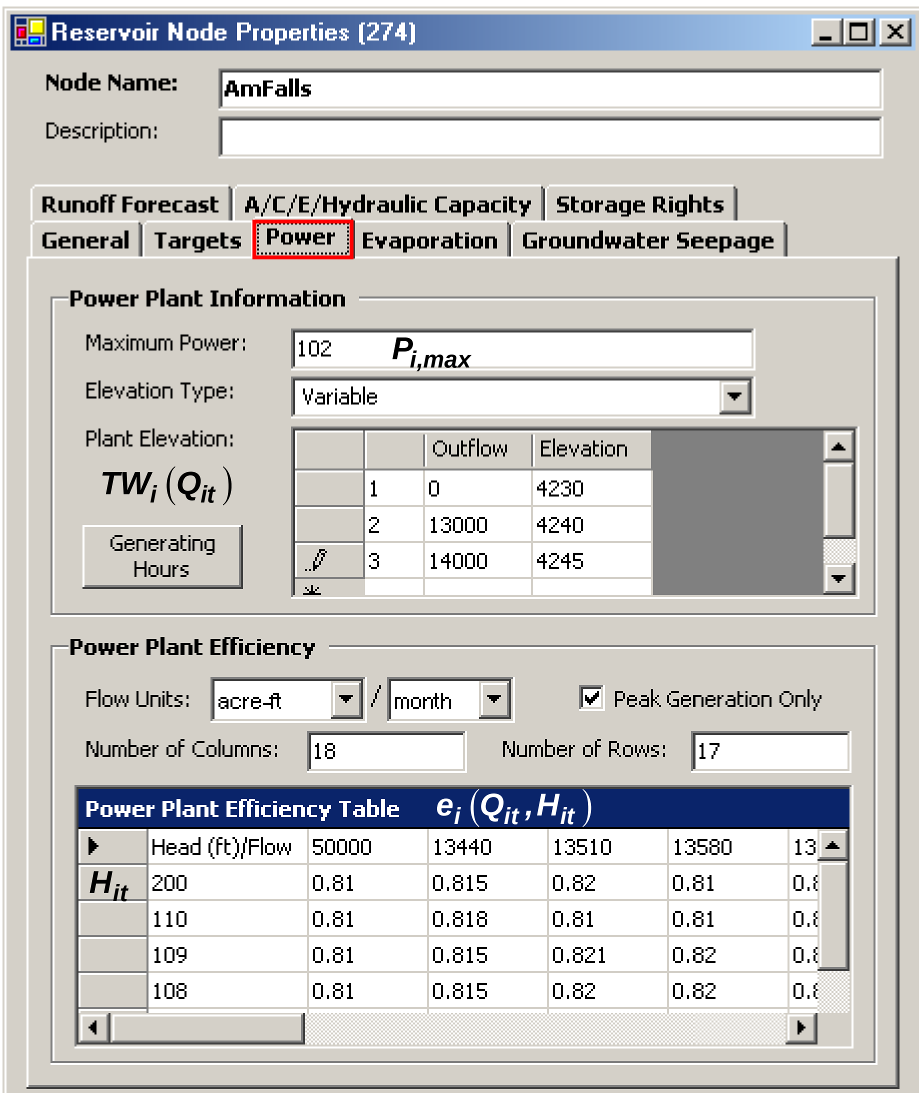


C. Hydropower

High-Head Power Plants. MODSIM computes both power capacity and energy generation in high-head power plants using the basic power equation:

$$P_{it} = K \cdot Q_{it} \cdot \bar{H}_{it} \cdot e_i \left(Q_{it}, \bar{H}_{it} \right) \le P_{i,\max} \tag{10}$$

where P_{it} is power output during period t (KW) ; Q_{it} is turbine release (volume/time period); $\bar{H}_{it}$ is mean effective head for time period t ; $e_i\left(Q_{it}, \bar{H}_{it}\right)$ is plant efficiency, interpolated from an efficiency table as a function of discrete release rates Q and heads H ; K is a conversion constant; and $P_{i,\max}$ is the maximum capacity of the power plant. The **Power** tab in the **Reservoir Node Properties** form displays power plant information.



For power plants with constant tailwater elevation; i.e., based on elevation of the power plant, mean effective head $\bar{H}_{it}$ is calculated as:

$$\bar{H}_{it} = 0.5 \cdot \left(E_i(S_{it}) + E_i(S_{i,t+1}) \right) - EP_i \tag{11}$$

where EP_i is power plant elevation (**Plant Elevation Type**: *Constant*) and $E_i(S_{it})$ is water surface elevation at the beginning of period t as interpolated from the area-capacity-elevation table for reservoir i.

For power plants influenced by tailwater elevations:

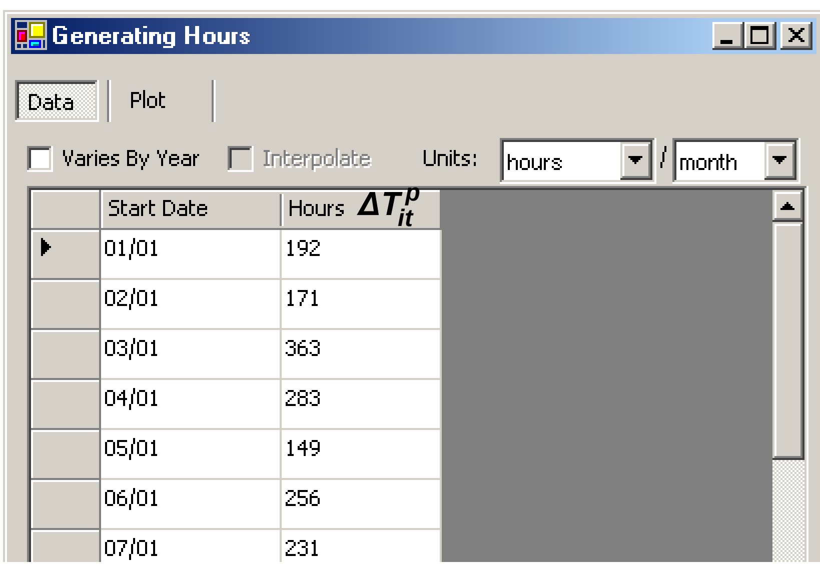
$$\bar{H}_{it} = 0.5 \cdot \left(E_i(S_{it}) + E_i(S_{i,t+1}) \right) - TW_i(Q_{it}) \tag{12}$$

where $TW_i\left(Q_{it}\right)$ is tailwater elevation interpolated from the outflow-elevation table for reservoir i (**Plant Elevation Type**: *Variable*).

Energy Generation. *On-peak* energy generation (MWH) is calculated as:

$$E_{it}^{p} = P_{it} \cdot \Delta T_{it}^{p} \tag{13}$$

where ΔT_{it}^{p} is total hours of on-peak generation in time period t, entered into the **Power** form under the **Reservoir Node Properties** form by clicking the **Generating Hours**.



Off-peak energy is calculated as:

$$E_{it}^{o} = P_{it} \cdot (\Delta T_t - \Delta T_{it}^{p}) \tag{14}$$

where ΔT_t is the total number of hours in period t. The **Power** form also includes a check box: *Peak Generation Only*, which when checked signifies that all discharges from the reservoir are assumed to occur only during the on-peak hours of generation. In effect, discharge rate during the on-peak hours only is now:

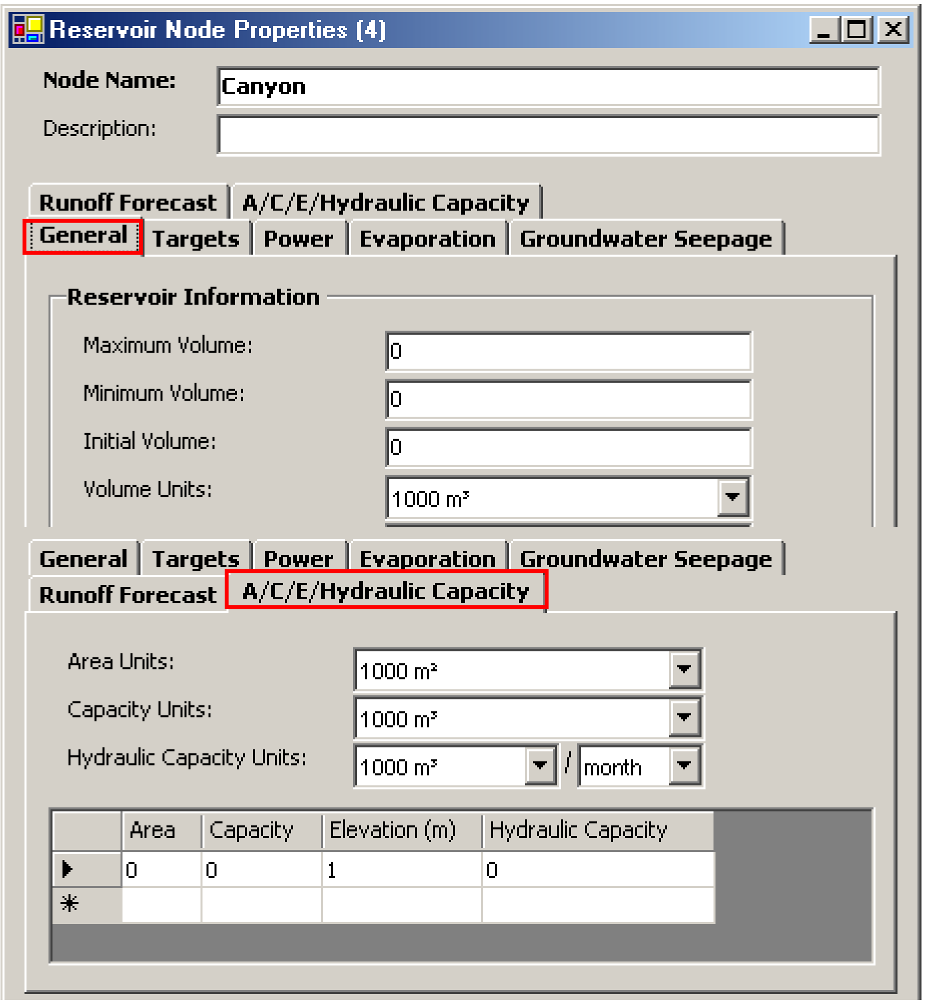
$$Q_{it}^{p} = Q_{it} \cdot \frac{\Delta T_t}{\Delta T_{it}^{p}} \tag{15}$$

where Q_{it} is the average discharge rate through the power plant in reservoir i during period t; and Q_{it}^{p} is the discharge rate occurring during the on-peak hours. This increases power capacity during the on-peak hours according to the following formula:

$$P_{it} = K \cdot Q_{it}^{p} \cdot \bar{H}_{it} \cdot e_i\left(Q_{it}^{p}, \bar{H}_{it}\right) \tag{16}$$

with energy calculated using Eq. 13. In this case, it is assumed that turbine releases occur during on-peak hours only. For these types of power plants, downstream re-regulation reservoirs with sufficient capacity for daily carryover storage are usually needed for providing consistent flow rates downstream. The unchecked *Peak Generation Only* box instructs MODSIM that releases can be made during off-peak hours.

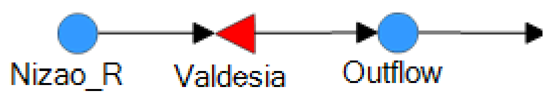
Run-of-the-River Power Plants. Low-head or run-of-the-river projects utilize turbines that require little head for generation. These are modeled in MODSIM by creating a zero capacity reservoir; i.e., a reservoir with no storage capacity. The corresponding area-capacity-elevation table has only a single entry with a nominal elevation value of 1, with power plant elevation set to 0, which establishes a constant unit valued head and the same

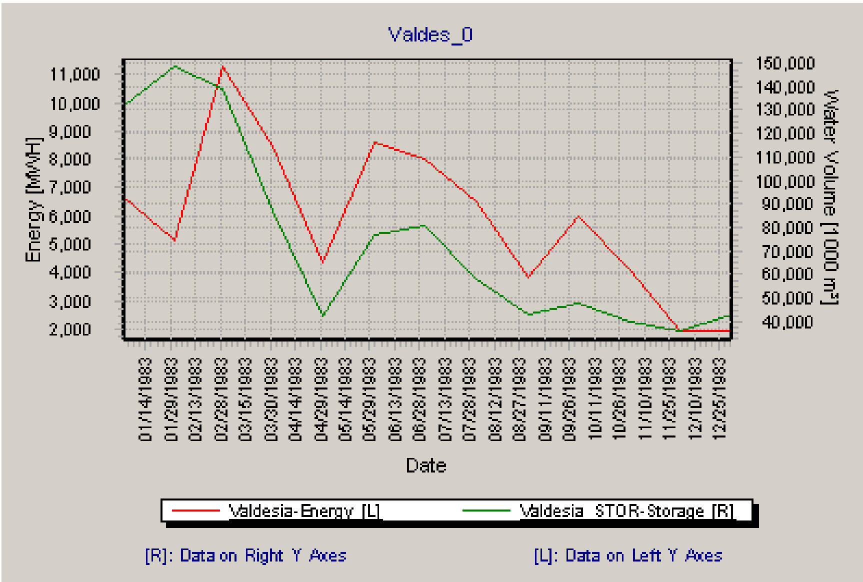


power equation as in Eq. 10 is utilized. Efficiency tables and generating hours can be entered as with high-head power plants.

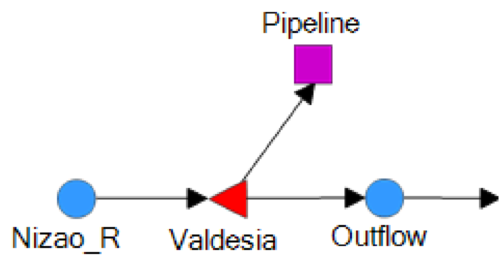
Pumped Storage. Pumped storage projects are indirectly considered by simply increasing the generation hours per period, even beyond the total actual hours in the period. This corresponds to increasing the *load factor* for the power plant. Although *load factor* is generally defined as *power used/peak power*, it can also be defined as *on-peak generation hours/total hours*. For pumped storage projects, the load factor may be > 1. In MODSIM, all hydropower plants are assumed downstream of storage projects.

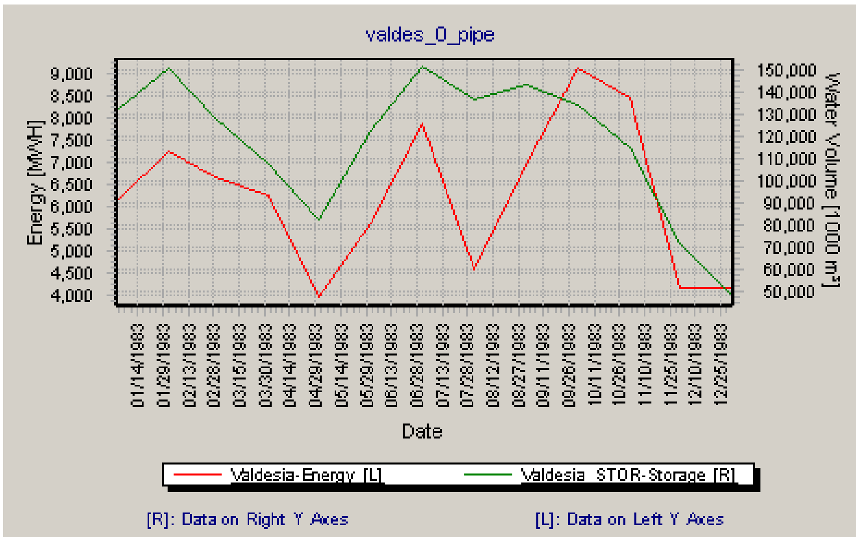
Power Plant Discharge. MODSIM assumes there is only one power plant associated with each reservoir, and a single discharge outlet representing penstock capacity. For the simple network below, there is only one outlet from the reservoir, so the results accurately represent the energy generation from the power plant.



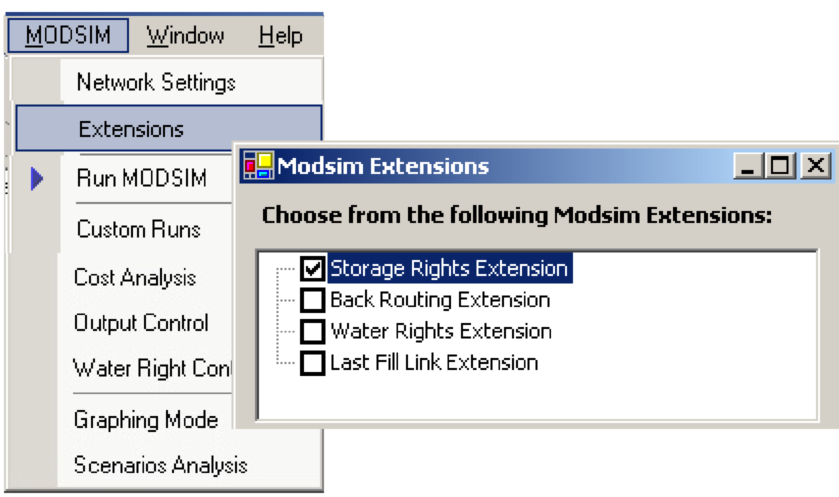


However, if there are multiple outlets from the reservoir, by default, MODSIM assumes that total discharge from all outlets passes through the power plant. Here, a water supply pipeline is delivering flow directly from the reservoir, but it can be seen from the results that even though the reservoir volume has decreased, energy generation is increased since the pipeline flow is incorrectly included in the assumed power plant discharge.

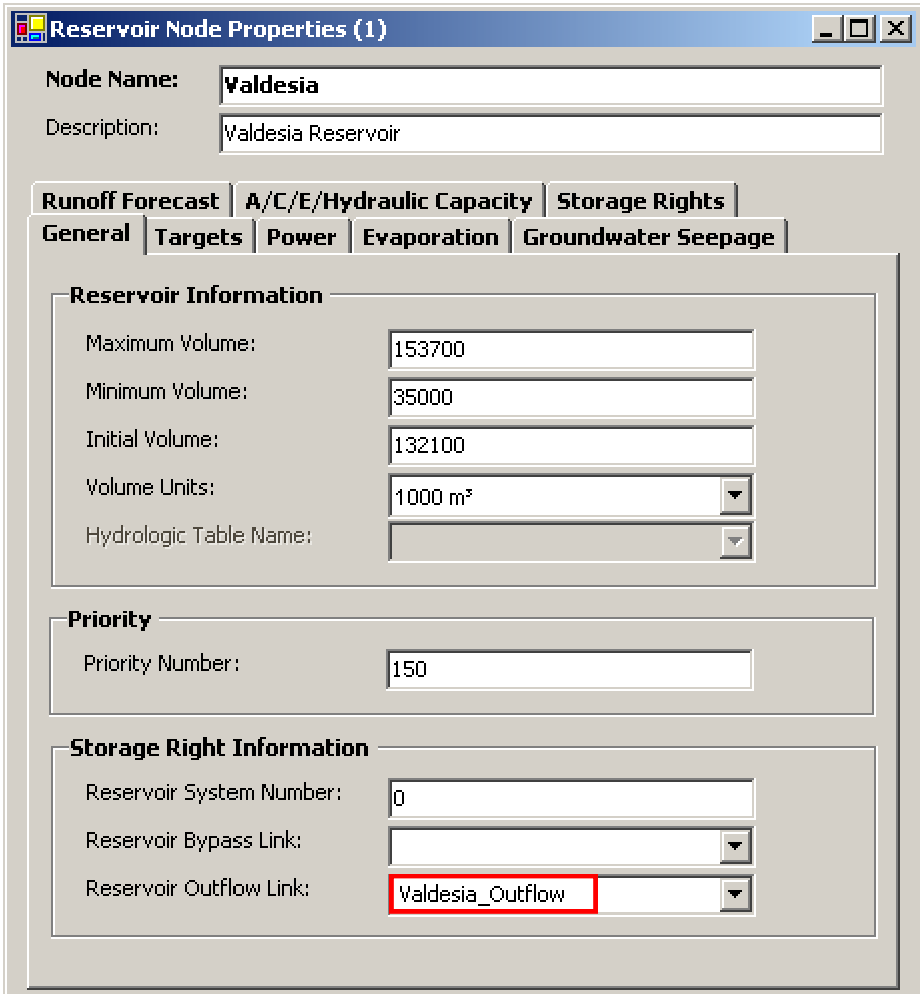




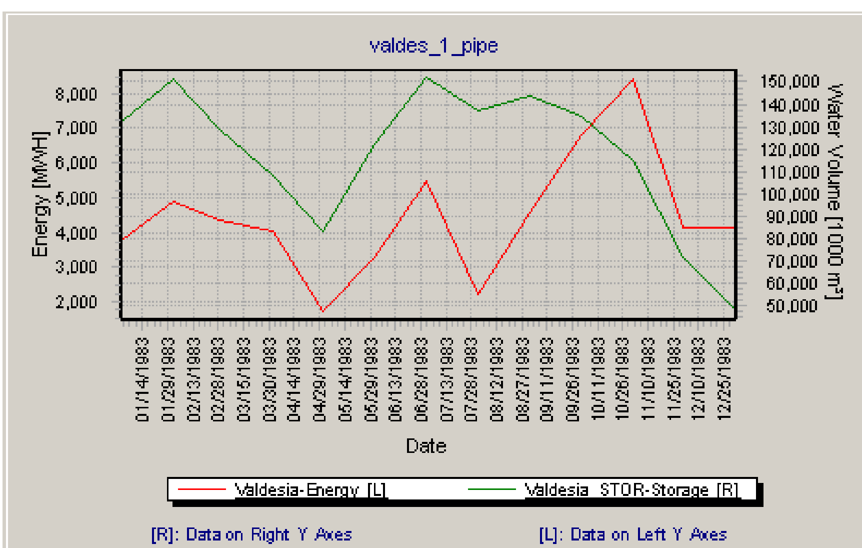
To overcome this problem, **MODSIM > Extensions** should be selected, which displays the **Modsim Extensions** form. Checking the **Storage Rights Extension** box provides a means of selecting the outflow link for the reservoir that will be used for generating hydropower.



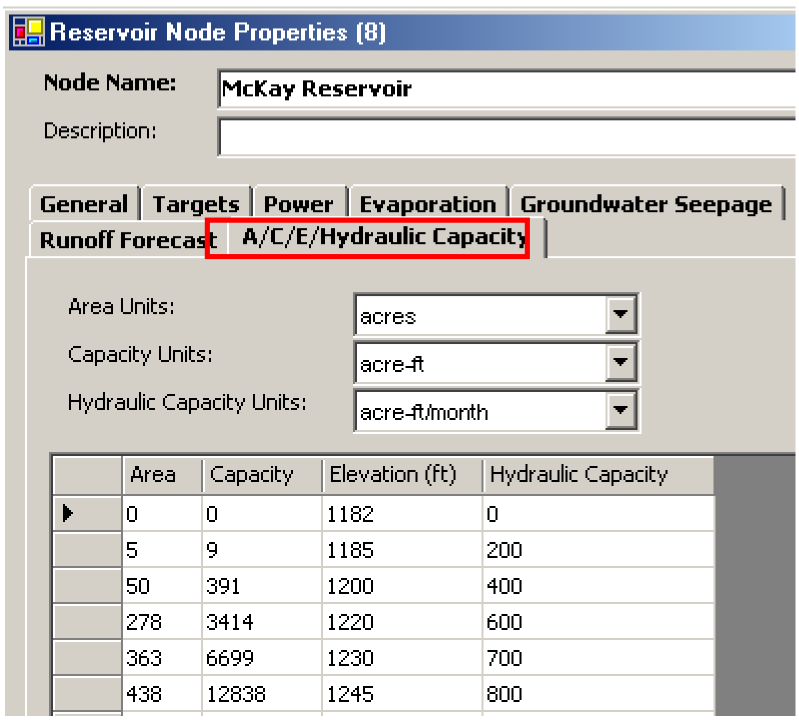
Opening the **Reservoir Node Properties** form reveals that a new field called **Storage Right Information** now appears under the **General** tab which allows specification of the *Reservoir Outflow Link*. Clicking the dropdown arrow, the outflow link "Valdesia_Outflow" is selected as shown.



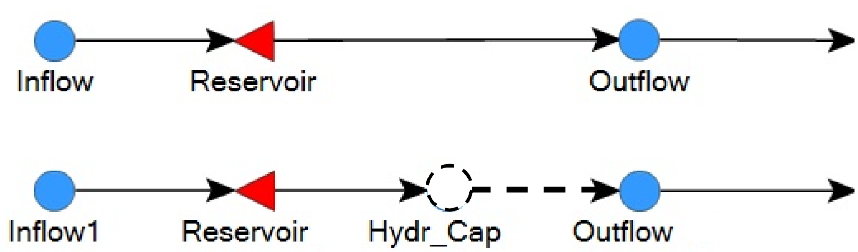
Execution of MODSIM with the outflow link specified in this way gives the following results, where energy generation is reduced since flow in the pipeline is now bypassing the power plant. Volume in the reservoir is the same as before since MODSIM is correctly releasing flows to the pipeline directly from the reservoir.



Hydraulic Outlet Capacity. Maximum available discharge capacity of reservoir outlet works is dependent on reservoir elevation and head. This dependency is accentuated for reservoirs with large capacity or simulation over short time steps (e.g., daily). MODSIM allows specification of hydraulic outlet capacity as a function of reservoir elevation, which is assigned as a restriction on the outflow link from the reservoir. When the Storage Rights Extension is activated and *Hydraulic Capacity* values are entered as a function of elevation, then MODSIM creates an artificial outlet node and an artificial hydraulic capacity link with the upper bound on flows iteratively adjusted according to average elevation in the reservoir over the current period. Be sure that the *Reservoir Outflow Link* is correctly specified in the **Storage Right Information** combo box under the **General** tab of the **Reservoir Properties** form. The name of the outflow link which is created is "(*Name of Reservoir)*_Nonstorage**x**", where **x** is the number of unnamed nonstorage nodes in the network.



Area	Capacity	Elevation (ft)	Hydraulic Capacity
0	0	1182	0
5	9	1185	200
50	391	1200	400
278	3414	1220	600
363	6699	1230	700
438	12838	1245	800



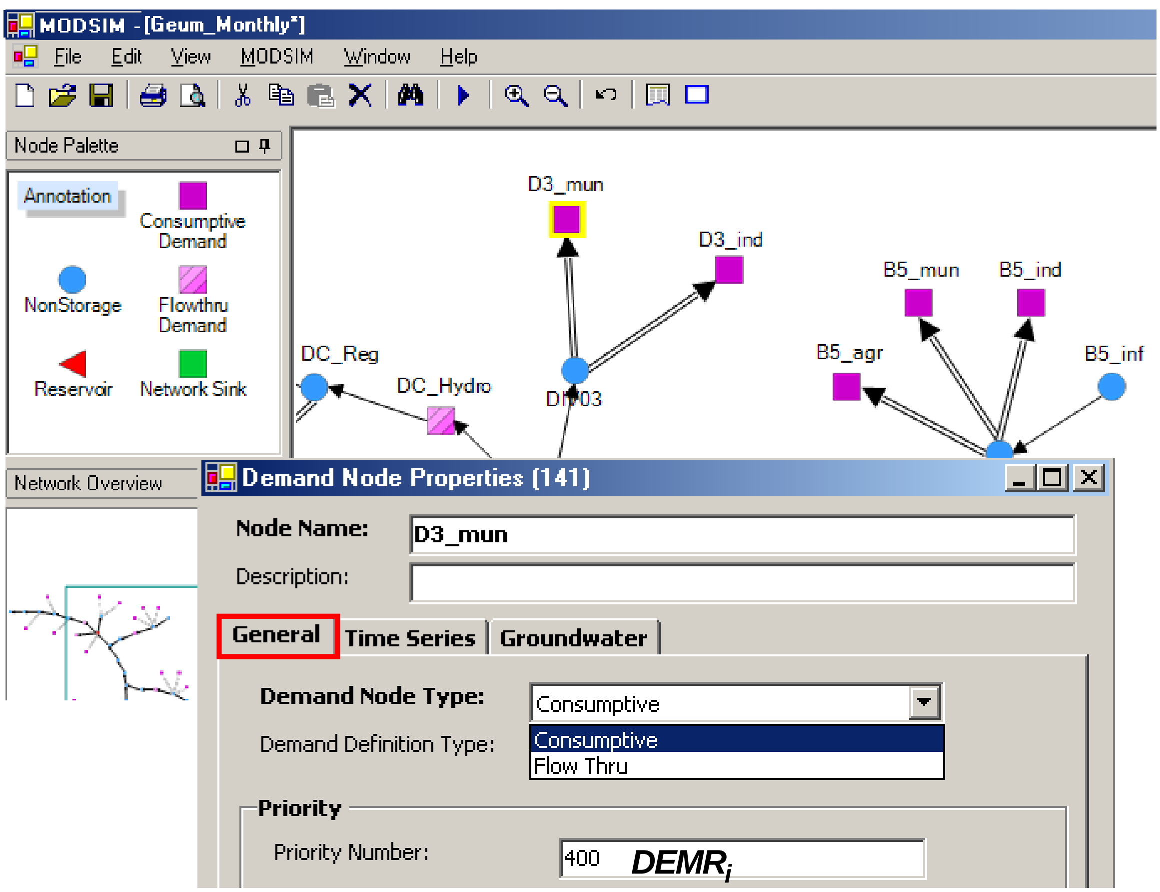
D. Demands

Consumptive Demands. As shown in Fig. 4, MODSIM automatically creates artificial demand links originating at each demand node and accumulating at a single artificial demand node **D**. The parameters for the artificial demand links are defined as $[0, D_{it}, c_k]$ for artificial demand link $k = [i, \mathbf{D}]$ originating from demand node i. Demands D_{it} may defined as: historical diversions, decreed water rights, predicted agricultural demands based on consumptive use calculations (performed outside MODSIM), or projected municipal and industrial demands. Link weights or costs on the artificial demand links are calculated as:

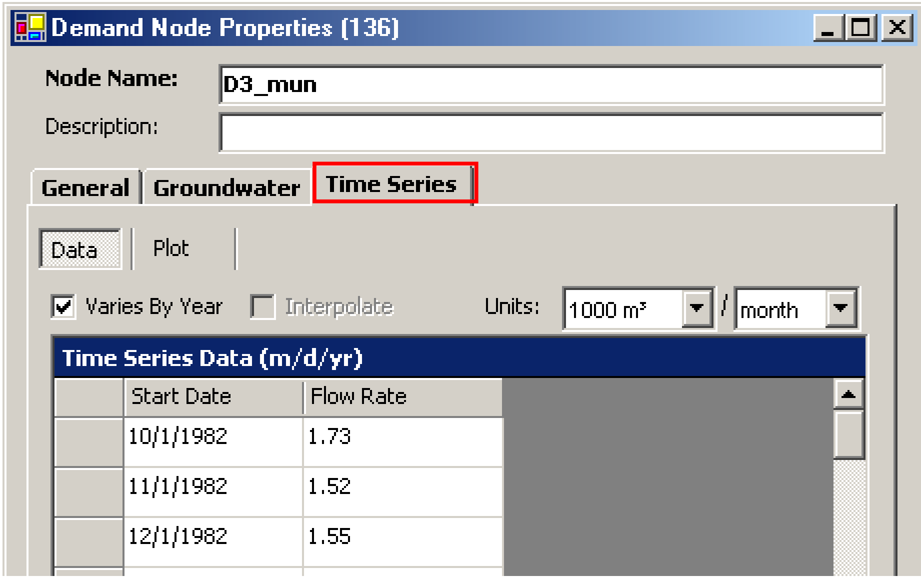
$$c_k = -\left(50000 - 10 \cdot DEMR_i\right) \tag{17}$$

where, similar to reservoir priorities, the user selects priorities $DEMR_i$ between 0 and 5000, with lower numbers representing higher priorities; i.e., larger negative costs.

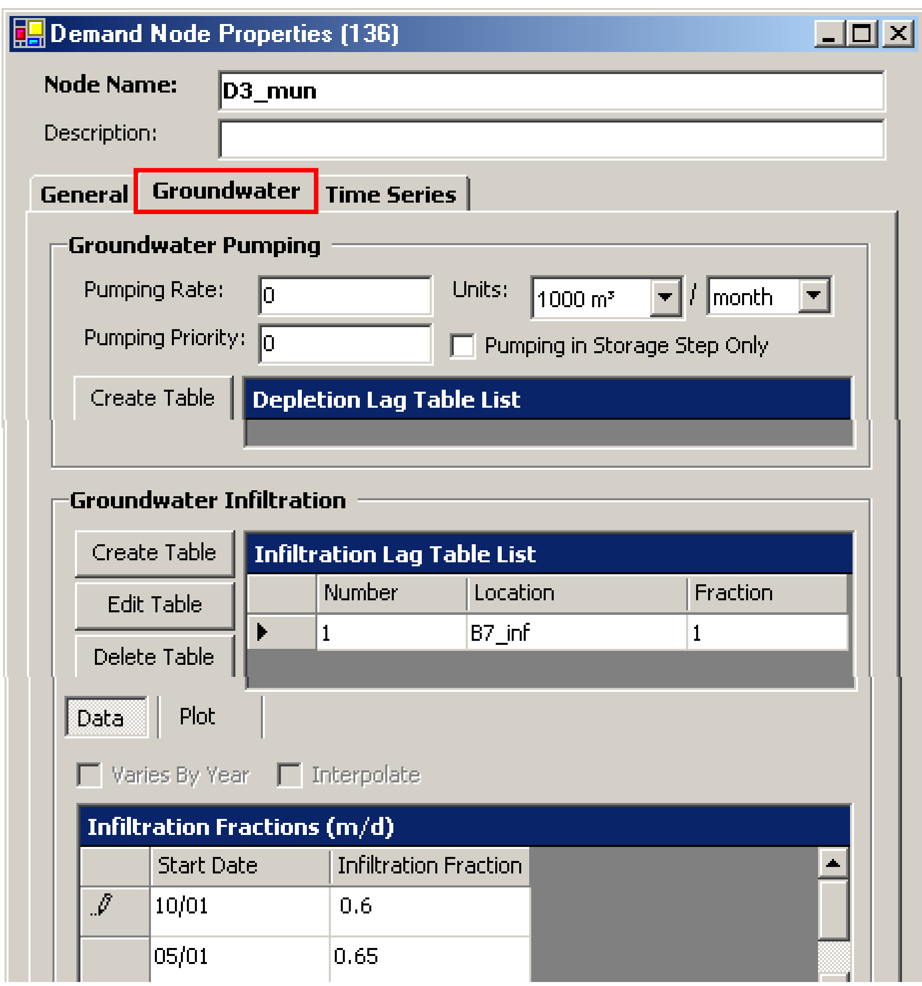
The **General** tab of the **Demand Node Properties** form provides for selection of two **Demand Node Types**: *Consumptive* and *Flow Thru*. *Consumptive* demands result in consumption of at least a portion of the flow diverted to the demand. Nonconsumptive *Flow Thru* (or *Flow-Through*) demands are designed to maintain instream flow requirements in priority for selected river reaches for environmental, ecological or navigation purposes. Priority number $DEMR_i$ is also entered under the **General** tab.



Clicking the **Time Series** tab displays the demand time series data, which can be input manually, with the **Time Series Import** tool, or through *copy* and *paste* operations.



The **Groundwater** tab allows entry of the *infiltration fraction* f_{it} as the portion of actual water delivery that infiltrates to groundwater, which equals (1 - *efficiency*). These



fractions are allowed to vary seasonally. The remainder of this form provides specification of information related to portions of the infiltration contributing to groundwater and appearing as downstream return flows, possibly at multiple locations. Details on stream-aquifer interactions, including both return flows and stream depletions due to groundwater pumping to supplement water supply to the demand node, are discussed in a subsequent section of this Manual.

Instream Flow Demands. MODSIM also provides for non-consumptive *flow-through* demands that are applied to *instream flow* uses such as navigation, water pollution control, fish and wildlife maintenance and recreation. The **Flowthru Demand** object can be dragged to the **Network Editor Window**, or an existing **Demand** object can be changed to a **Flowthru Demand** in the **Demand Node Properties** form, which also changes it to a **Flowthru Demand** object . As seen in Fig. 12, specifying a **Flowthru Demand** object creates a new **Flow Thru** tab in the **Demand Node Properties** form which provides for specification of the **Flowthru Node(s)**. That is, the *Flow Thru* demand **AndPowr** removes flow (in priority) from *Node39* and returns it, without loss, to downstream node *ANDI*, essentially simulating . The use of flow-through demands for minimum streamflow requirements has two primary advantages: (i) the flow-through

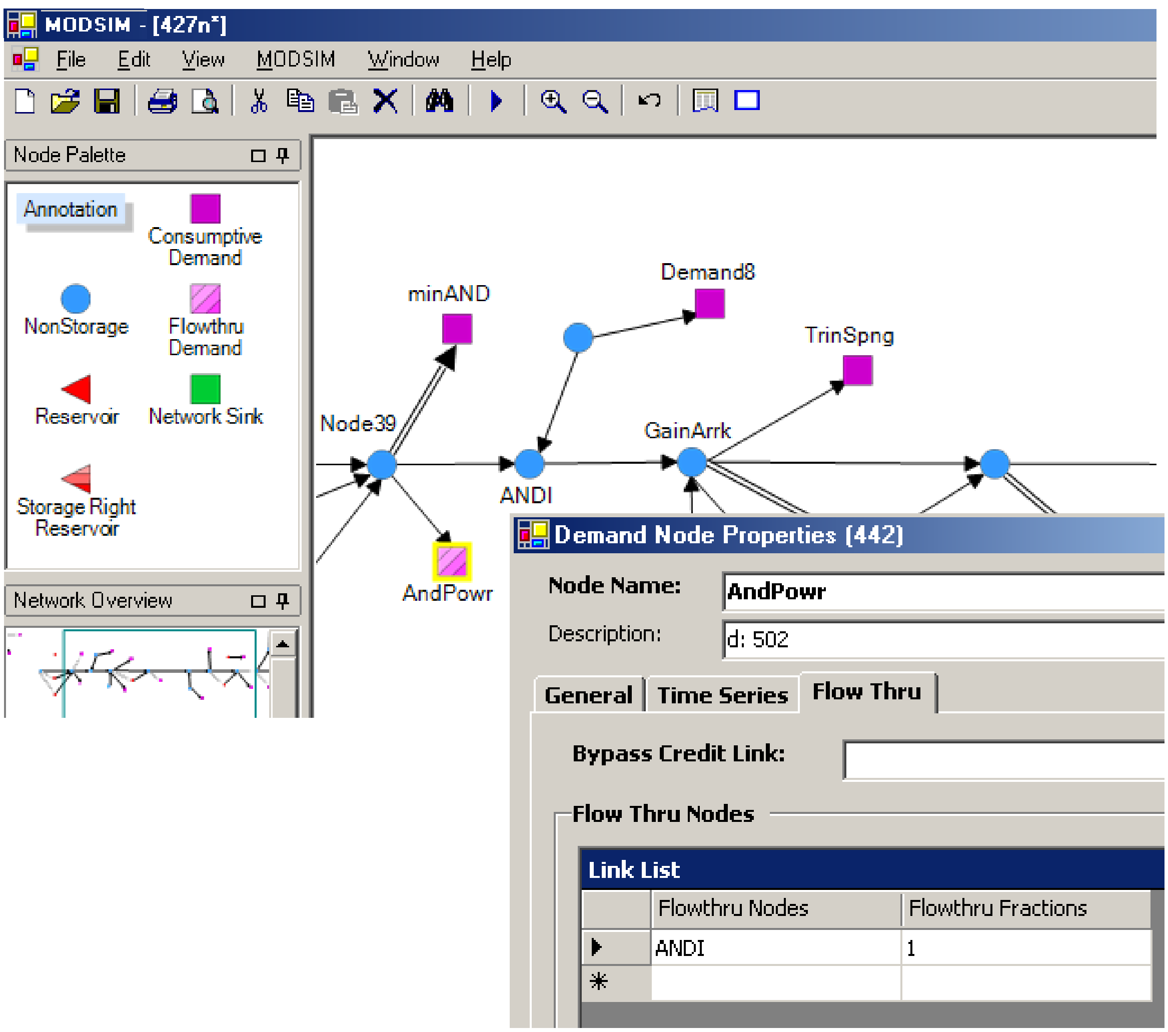


Fig. 12. Illustration of *flow-through* demand in the Upper Snake River basin network.

demand can be assigned a priority in relation to any other demand in the basin, and (ii) simply setting a fixed lower bound on the link corresponding to a minimum streamflow requirement can result in the MODSIM network algorithm prematurely terminating at an infeasible solution if there is insufficient flow available to satisfy the minimum streamflow requirement. The flow-through demand can receive a shortage similar to any other demand, depending on the relative ranking of the water right priority assigned to it. An additional advantage of the flow-through demand is that it may be used to divide flow according to predetermined fractional distributions, rather than water allocation priorities.

As illustrated in Fig. 13, *flow-through* demands operate by iteratively removing flow as a demand from the network, but then replacing the flow at one or more specified (usually the next downstream) node(s) in the next iteration, which essentially corresponds to a demand with 100% return flow which is unlagged. The *superscript* ℓ in Fig. 13 represents an iteration counter, since flow-through demand returns must be calculated through a successive approximations procedure. In the first iteration, the instream flow demand D_2 is treated as a consumptive demand and flow is delivered according to priority through solution of the network algorithm. At the next iteration, the flow $q_{2\mathbf{D},t}^{(\ell-1)}$ actually delivered in link [2,**D**] in the previous iteration is then added as an inflow to node 3, and the network is solved once again, but with the bounds on link [2,**D**] adjusted to only remove additional flows above what was already flowing (i.e., $q_{23,t}^{(\ell-1)}$) in the instream flow reach [2,3] in the previous iteration. In this case, link [2,3] is referred to as a **Bypass Credit Link**, since it is only necessary to augment the streamflow above the

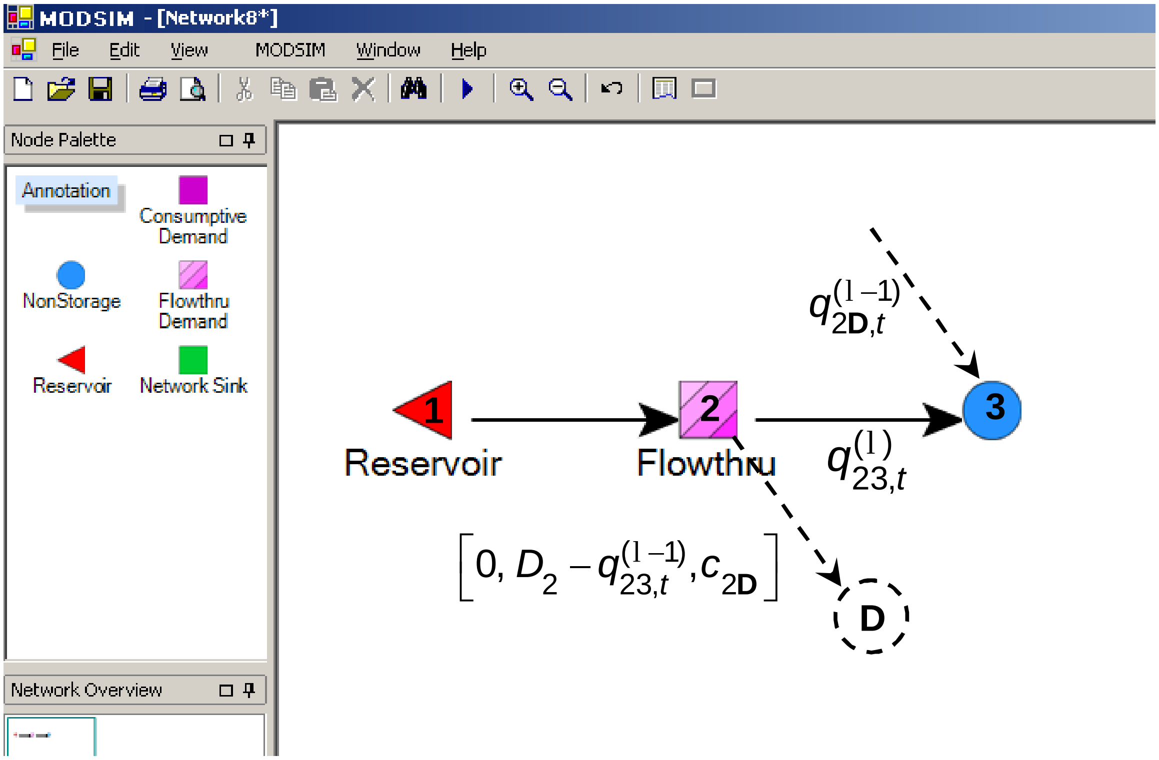


Fig. 13. Illustration of Flow-Through Demands

current flow level so as to satisfy the minimum streamflow requirement. This solution process continues until successive estimates of returns to node 3 agree. Note that the flow in link [2,3] does not actually represent the total instream flow. Flows leaving node 3 would better represent the actual flows in link [2,3] , assuming there are no other demands or inflows at node 3. The output report for demand node 2 properly considers the actual flow in link [2,3] as related to the instream flow requirement.

Fig. 14 shows an example of a flow-through demand for a network constructed for the Snake River Flow Augmentation Study conducted by the U.S. Bureau of Reclamation and U.S. Army Corps of Engineers (USBR, 2000). This study examined potential scenarios for reallocation of flows to satisfy instream flow requirements for endangered species in the Snake River basin. A **Flow-Thru** demand is established at node *AndPowr* which accrues flow back to the river reach at node *ANDI* in the same time step, and without consumptive loss. The specified bypass credit link is *_39_ANDI* such that the flow-through demand is only used to augment flow in this link to satisfy minimum streamflow requirements. The time series of instream flow requirements is entered at the *Time Series* tab, and the associated priority associated entered at the **General** tab.

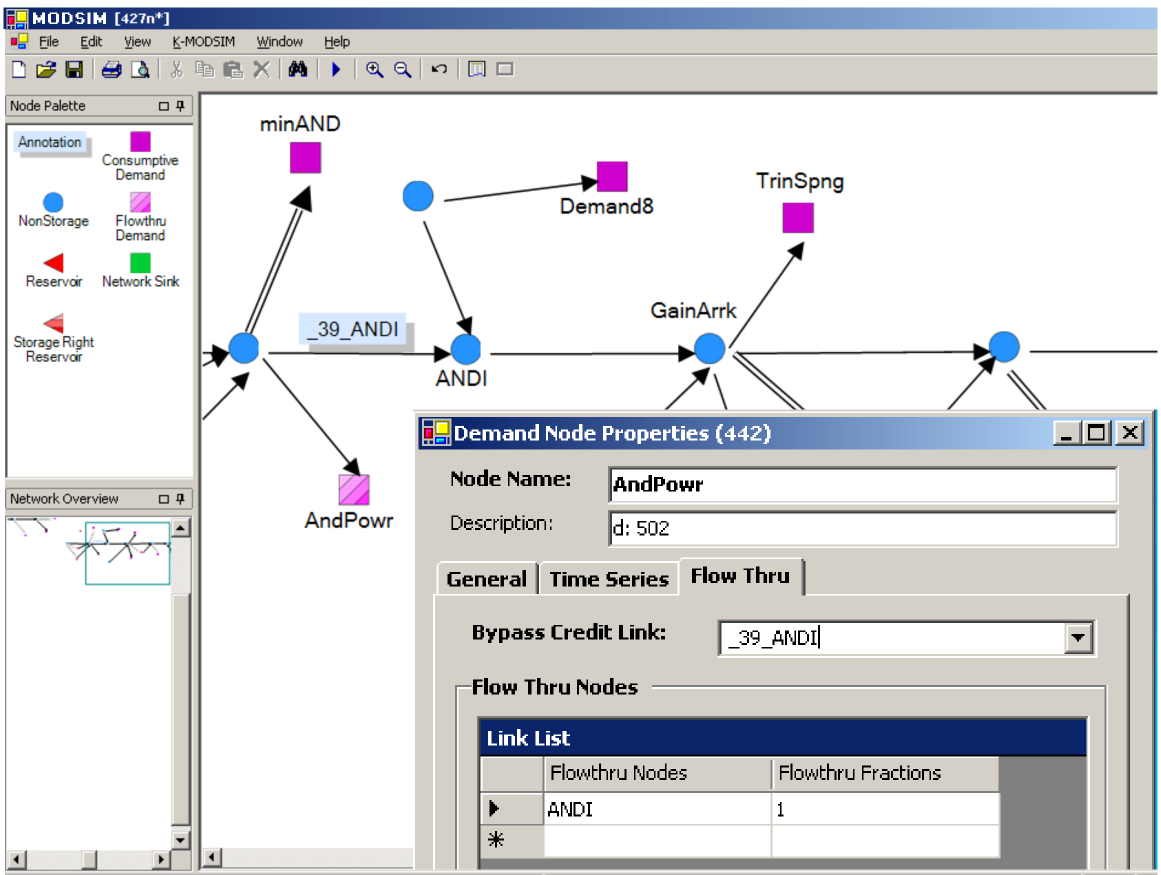


Fig. 14. Illustration of *flow-through* demand in the Upper Snake River basin network.

An additional advantage of the flow-through demand is that it may be used to divide flow according to a predetermined *fractional distribution*, rather than based on demand priorities. This is useful for mutual irrigation companies, or other mechanisms for apportioning flow in a river basin. Flow-through demands are also valuable for model calibration purposes, where a flow-through demand is located at a streamflow gaging station site, and the demands assigned to the flow-through demand node correspond to historical measured flows, which are assigned as the highest priority in the basin. MODSIM parameters and unknown system gains and losses can then be adjusted until measured flows at the gaging station are reasonably matched.

Shortage Rules. During higher than normal flow conditions in a river basin, all demands are generally satisfied, whereas during low flow and drought conditions, severe shortages may occur. The priority structure embodied in MODSIM distributes available water supply to high priority uses first. In some river basin systems, the administrative goals are to produce a more equitable sharing of available water during drought. Simply assigning the same priorities to all demands in the basin will not necessarily result in an equitable distribution in a MODSIM solution. Rather, without any priority guidance, MODSIM will produce inconsistent solutions and random distribution of available water. However, similar to use of Hydrologic State tables for defining conditional reservoir operating rules, demands can also be conditioned on Hydrologic State information, allowing development of *shortage rules* that attempt to equitably share flow deficiencies among water users during periods of extended drought or low-flow conditions. As seen in Fig. 15, basin-wide demands can be reduced by certain percentages as conditioned on the Hydrologic State, allowing more equitable sharing of available water resources during dry periods.

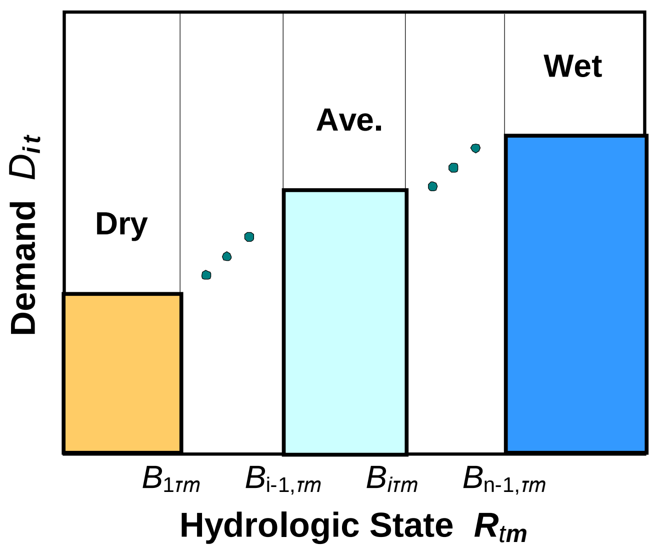


Fig. 15. Shortage rules conditioned on Hydrologic state.

Shortage rules are defined in MODSIM by selecting a **Hydrologic Table** name in the **General** form within the **Demand Node Properties** form, as in Fig. 16. Click **Apply** and **OK** after selection of the *Hydrologic Table Name*, reopen the **Demand Node Properties** form, uncheck the *Varies by Year* box, and specify the shortage rule for each period, as seen in Fig. 17.

Conditional Reservoir Release Rules. In some cases, it is desirable to specify *conditional release rules* for reservoir operations rather than *conditional storage target rules* for each time period. This is easily accomplished by specifying an additional *flow-through demand* node downstream of a reservoir with the desired release levels designated as flow-through demands. These releases can be dependent on storage levels by using the *Hydrologic State* option for flow-through demands.

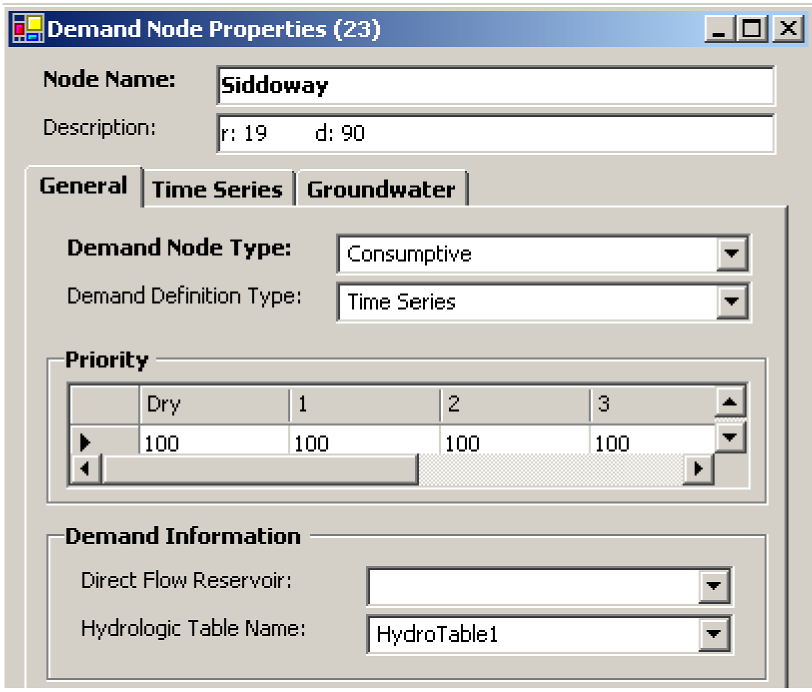


Fig. 16. Specification of *Hydrologic Table* for shortage rule.

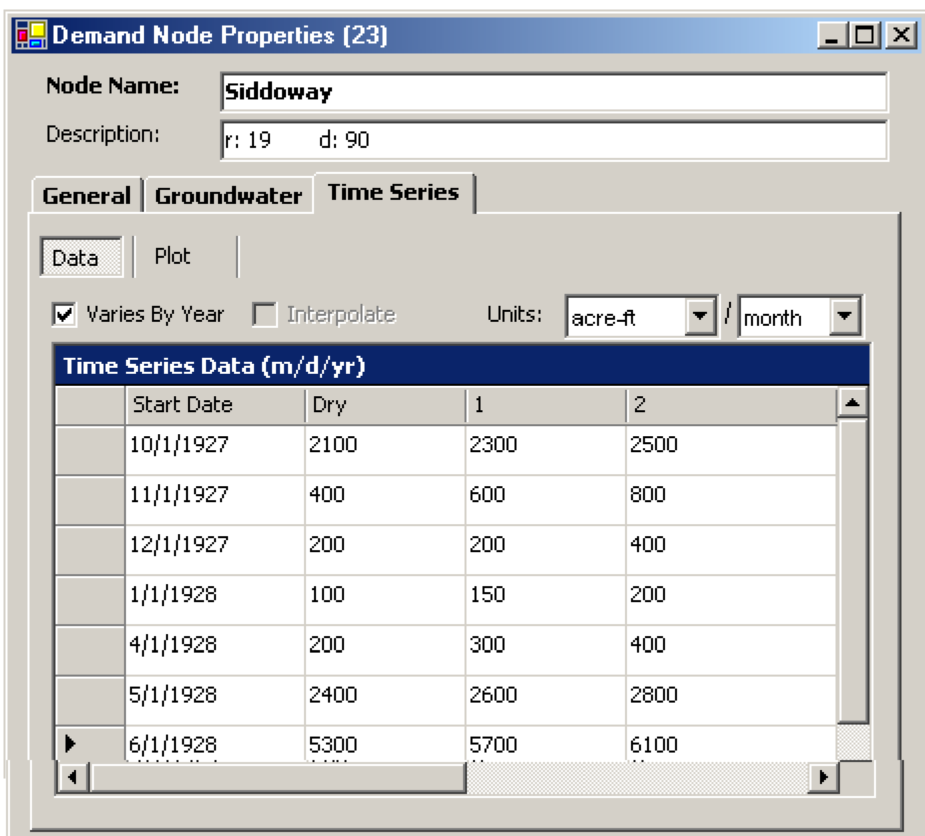
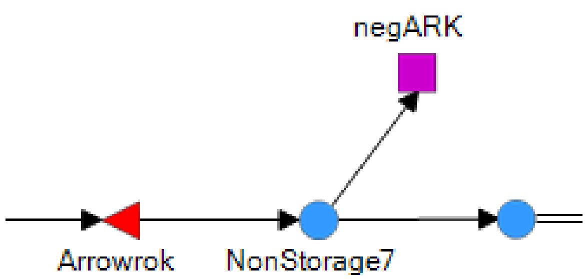


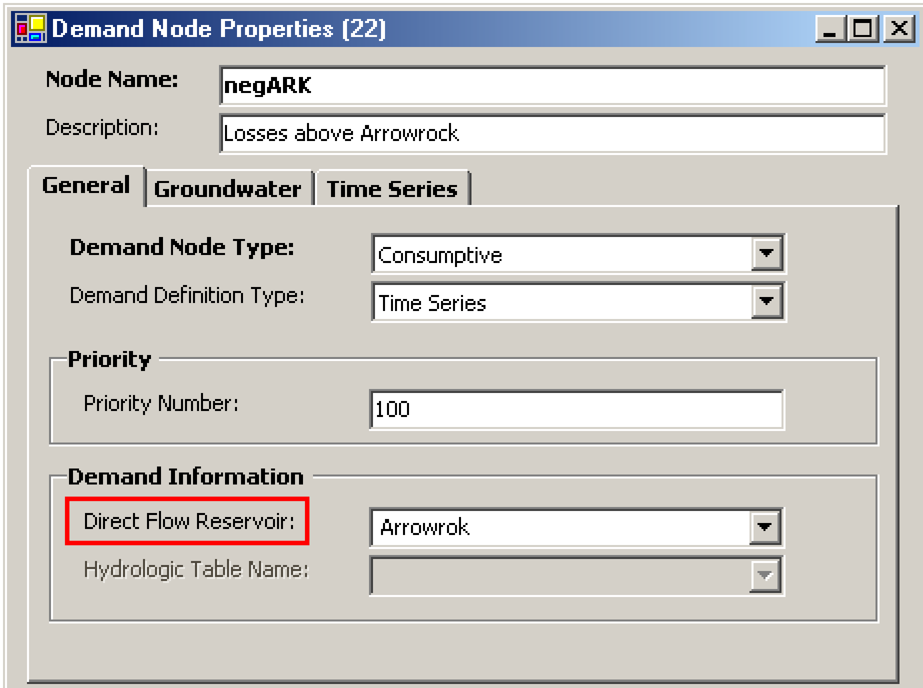
Fig. 17. Specification of shortage rule in **Demand Node Properties** form.

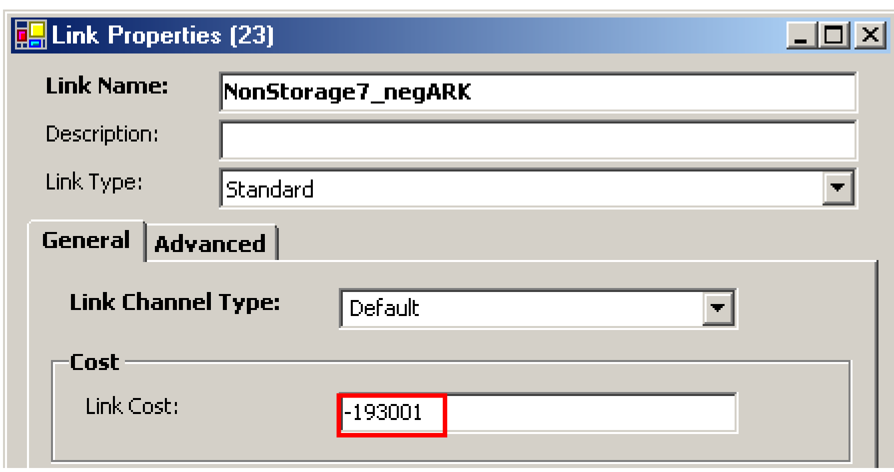
Direct Flow Reservoir Node. If a demand diverts water directly from a reservoir, the user should place the demand either upstream or downstream of the reservoir rather than directly at the reservoir. If an upstream location is selected, the demand will be unable to divert water directly from reservoir storage and must depend entirely on available flows in the upstream river reach. This may be appropriate if the demand is physically located near the headwaters of the reservoir and cannot depend on the reservoir storage for delivery. If the demand requires direct access to the reservoir storage to be satisfied, it should be placed downstream of the reservoir and the **Direct Flow Reservoir** field in the **Demand Node Properties** form set with the name of the reservoir. This assures that the diversion will be subtracted from the reservoir outflow for proper physical operational simulation. The demand can be specified as either a flow-through or consumptive demand.

If the **Water Rights Extension** is activated, then the link conveying flow to the demand can be specified as either a *Standard* or *Natural Flow* link. Use of the **Direct Flow Reservoir** function is particularly important if there are hydraulic outlet capacity restrictions on the reservoir. In this case, the artificial hydraulic capacity node created internally by MODSIM between the reservoir and the physical outlet node (see pg. 40) is designated (for computational purposes) as the FROM node for the link conveying flow to the demand. This means that direct flow from the reservoir to the demand is accomplished without any restrictions on hydraulic outlet capacity, thereby simulating direct withdrawals from the reservoir. This construct can also be applied if the reservoir happens to be a storage right reservoir, which is created with activation of the **Storage Rights Extension** under **MODSIM > Extensions**. However, care must be taken in this case since the impact of direct withdrawals from the reservoir can have uncertain consequences on the storage ownership accounts held in the reservoir.

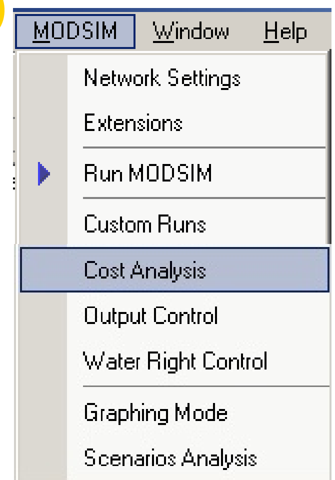
In this example, Arrowrock Reservoir in the Boise River system, Idaho, has hydraulic outlet capacity restrictions, thereby requiring it to be specified as a **Direct Flow Reservoir** for the *negARK* demand. The demand, in this case, represents precalculated losses in the reservoir and the upstream river reach due to evaporation and seepage. The link *NonStorage7_negARK* conveying flow to the *negARK* demand is assigned a very high negative cost to assure that these losses are correctly accounted for and given priority over all other demands. With designation of *Arrowrok* as the **Direct Flow Reservoir**, diversions to the *negARK* demand are taken directly from the reservoir without restrictions on hydraulic outlet capacity being imposed.



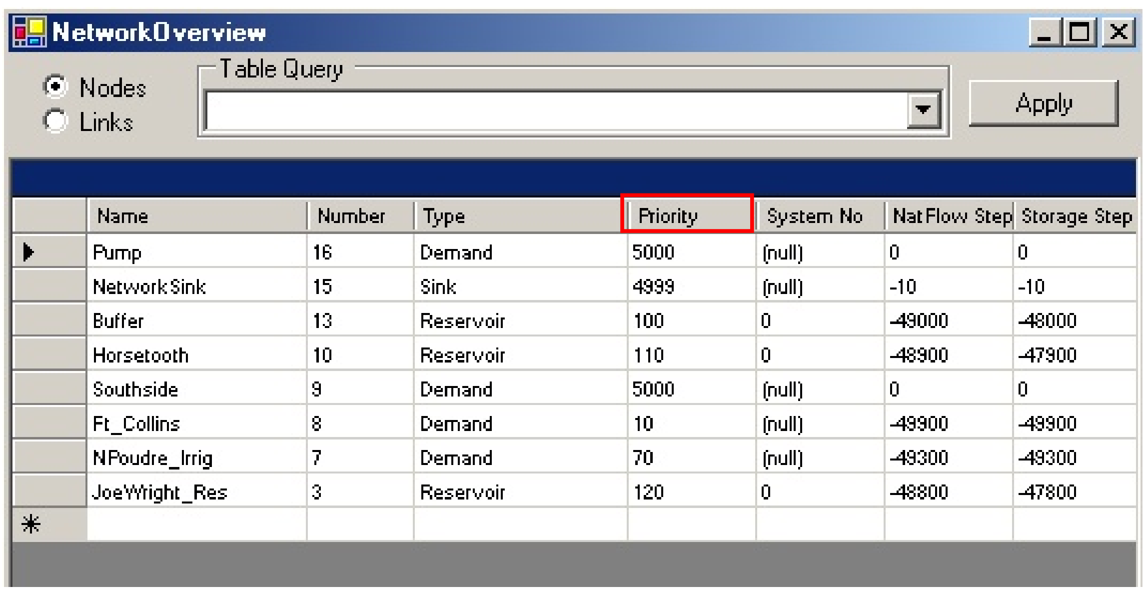

Demand Node Properties (22)
Node Name:
negARK
Description:
Losses above Arrowrock
General
Groundwater
Time Series
Demand Node Type:
Consumptive
Demand Definition Type:
Time Series
Priority
Priority Number:
100
Demand Information
Direct Flow Reservoir:
Arrowrok
Hydrologic Table Name:

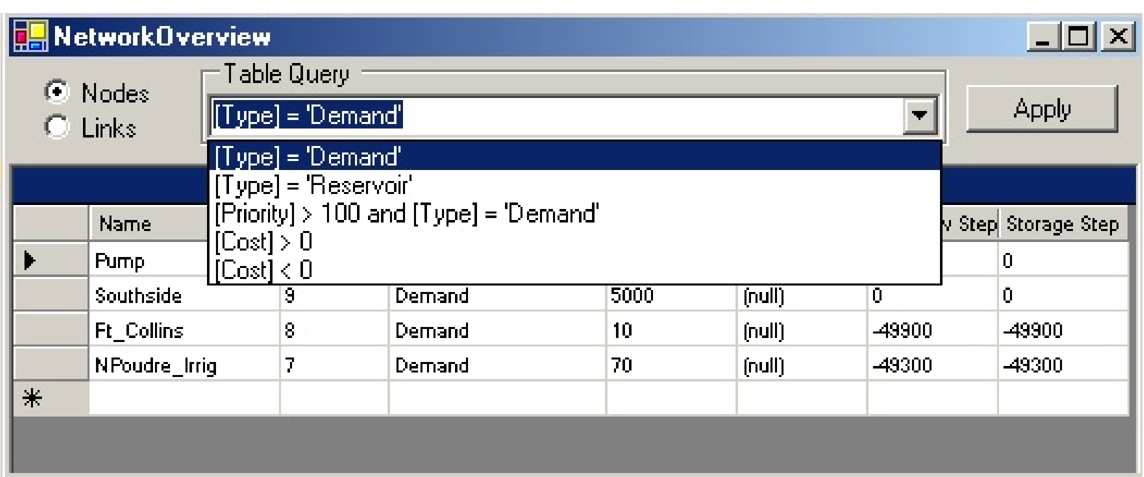

Link Properties (23)
Link Name:
NonStorage7_negARK
Description:
Link Type:
Standard
General
Advanced
Link Channel Type:
Default
Cost
Link Cost:
-193001

E. Editing Reservoir and Demand Node Priorities



For large networks with numerous demand and reservoir nodes, it is inconvenient for users to select each node individually for editing properties, particularly when it is necessary to compare priorities assigned to the nodes. Clicking **MODSIM > Cost Analysis** displays the **Network Overview** form providing a tabular listing of all nodes and links in the network. Clicking the radio button next to *Nodes* lists all demand and reservoir nodes and gives information on the node *Type* and *Priority*, as well as additional information related to storage accounts in the network which is discussed subsequently. As a convenience, any node *Priority* can be directly edited in this form without having to select the node object in the *Network Editor Window* and display its Properties form. In addition, a number of *Table Queries* are available for displaying only those nodes that satisfy particular criteria for evaluation.





VI. FLOW CONVEYANCE AND ROUTING

A. Channel Capacities

As seen in the **Link Properties** form shown in Fig. 18, MODSIM allows users to input constant flow capacity limits for each link, or varying daily, weekly or monthly maximum flow limits for specified *variable capacity links*. The latter are useful for considering seasonal influences in channel capacities and maintenance schedules. For example, the *JoeWright_Res_Poudre_R* link is a channel located high in the Rocky Mountains of Colorado. During the winter months, snow and ice restrict flows in the channel. In other regions, seasonal restrictions may be caused by scheduled maintenance, growth of algae, etc. In addition, a **Seasonal Capacity** can be specified, where the link is constrained to an annual maximum total seasonal flow, perhaps based on water rights. Once the accumulated seasonal flows exceed the maximum seasonal capacity, the link is effectively *turned off* and no further flows through that link are allowed throughout the

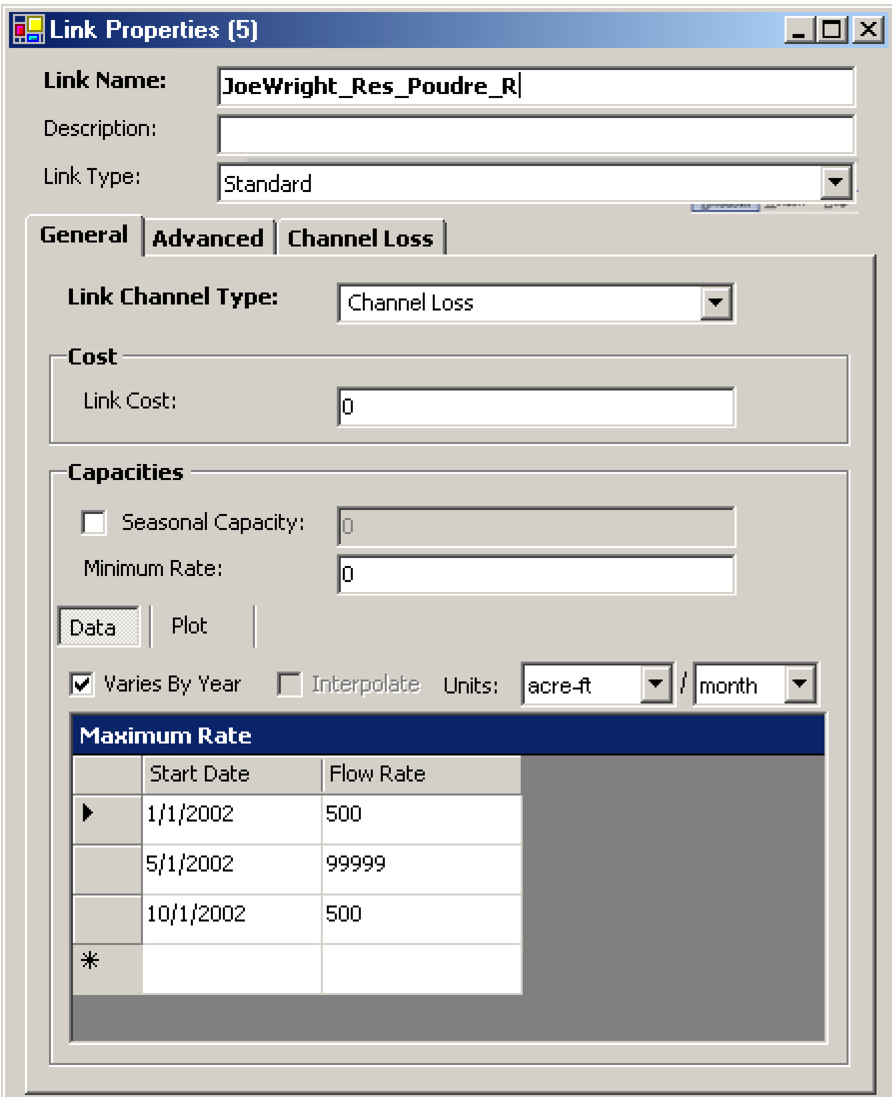


Fig. 18. Specification of channel capacity in *Link Properties* form.

remainder of the current season. Seasonal flow capacities are then reinitialized to the specified seasonal capacity at the beginning of the next season.

All links in the network must be bounded from above and below in MODSIM. Constant minimum flow capacities may be assigned to any link in the network, but care must be taken to avoid infeasible solutions. Improperly assigned minimum and maximum flow capacities on links are the major reasons for network solutions terminating in infeasibility errors. For minimum streamflow requirements, it is best to utilize the *flow-through* demand construct, as discussed previously.

B. Channel Losses

Links where channel losses occur are defined by specifying **Link Channel Type** in the **Link Properties** form as **Channel Loss**, which creates a new tab of the same name in the form. A *successive approximations* iterative procedure is employed in MODSIM for calculating channel losses, as illustrated in Fig. 19. First, network flows are initially

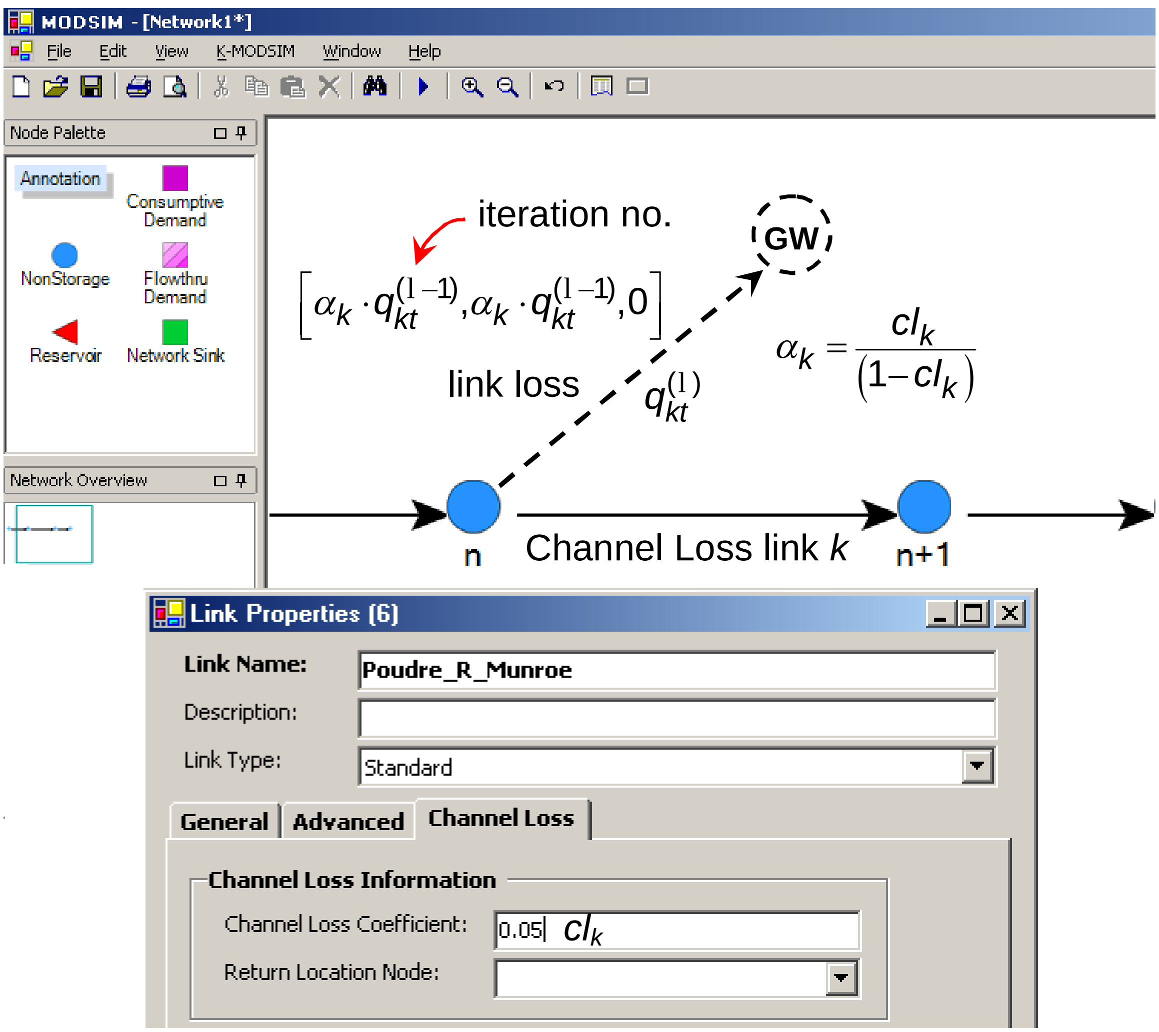


Fig. 19. Successive approximations procedure for channel loss calculations.

solved via the Lagrangian relaxation algorithm with *no losses* assumed, giving flows $q_k^{(0)}$ in link *k*. Since the user-specified loss coefficient cl_k represents the fraction of flow at the head of link *k* that is lost during transition through the link, then during any iteration ℓ, the current flow $q_k^{(\ell)}$ in link *k* is the flow remaining in the channel after losses have been removed. That is:

$$cl_k \cdot \left(q_k^{(\ell)} + ch.loss \right) = ch.loss$$

or

$$ch.loss = \left[\frac{cl_k}{(1 - cl_k)} \right] \cdot q_k^{(\ell)} = \alpha_k \cdot q_k^{(\ell)} \tag{18}$$

Coefficient α_k is applied to current link flows $q_k^{(\ell)}$ (after channel losses are removed) for calculating the losses. As shown in Fig. 19, this loss is removed during the next iteration by an artificial link terminating at the artificial groundwater **GW** node with both lower and upper bounds set equal to the current estimated channel loss. The network flow algorithm is then solved again. If current losses in link *k* agree with those found in the previous iteration ℓ - 1, then convergence has occurred. Otherwise, the procedure is repeated with the channel losses updated using Eq. 18, and specified as new bounds on the artificial channel loss link. This process continues until successive link loss estimates agree within a specified error tolerance. Notice that the **Channel Loss** tab allows specification of a **Return Location Node** if channel losses infiltrate into the connected stream-aquifer system and can return as surface flow at a downstream location. Return flow processes are governed by the groundwater modeling capabilities of MODSIM, which are discussed subsequently.

C. Multilinks

The multilink structure of MODSIM allows certain kinds of nonlinear functional relationships to be included in the network model. For example, Fig. 20 shows an example where channel losses in a reach change in a nonlinear relationship with flow rate in the channel. This nonlinear relationship is approximated with a piece-wise linear function, with each linear segment represented as a link connecting the same two nodes *i* and *j*. The capacities of each link represent the incremental flow change in that segment, and small unit costs are assigned to each link, with costs increasing with increasing flow. These costs, or perhaps better represented as *penalties*, are small enough that it is unlikely they will influence the overall distribution of flows in the network. However, they guarantee that link 1, associated with piece-wise segment 1, will fill first, followed by link 2, and finally link 3, as a result of solution by the minimum cost network flow algorithm employed in MODSIM. The accumulated flow in all three links represents the total flow in the channel connecting nodes *i* and *j*. It should be noted that any costs assigned to network links are treated directly as costs, and not priorities which are translated into costs using Eq. 4 or Eq. 17.

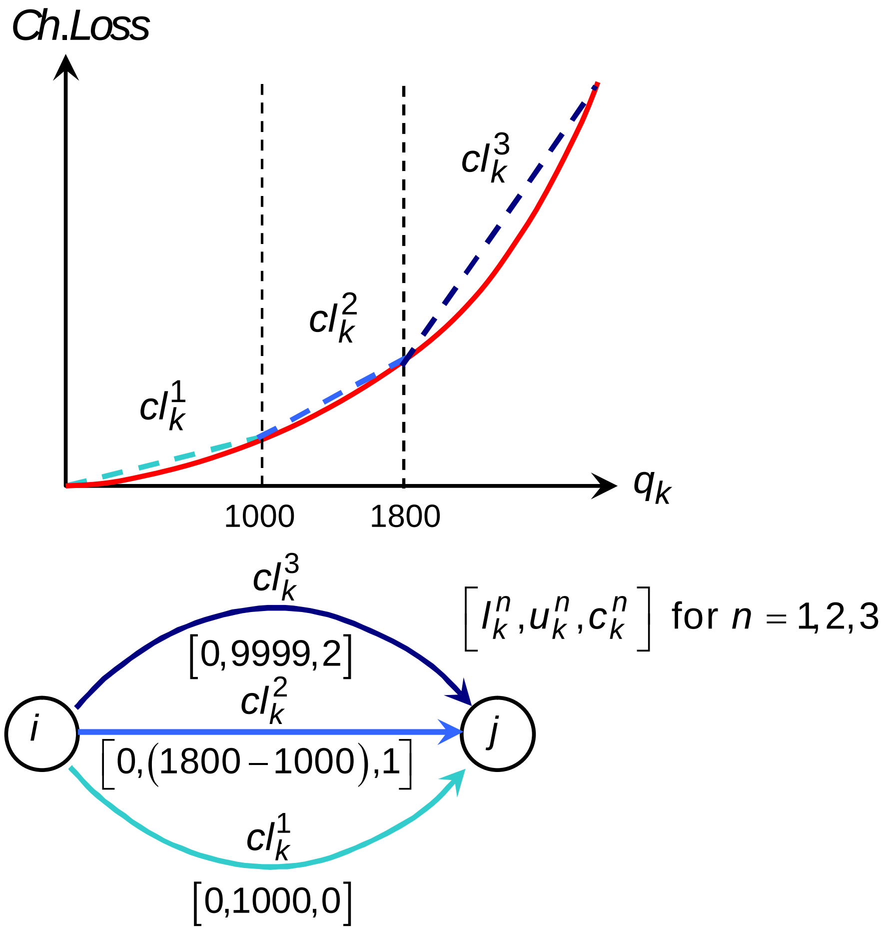


Fig. 20. Illustration of piece-wise linearization of channel loss as nonlinear function of flow using a multilink.

Clinking **Convert to MultiLink** on the context menu for any link allows creation of any number of links connecting the same two nodes, as in Fig. 21. Editing of the parameters of each link is easily accomplished, as shown in Fig. 22 for link 1 in the above example, where the flow increment for that segment of the piece-wise linear function is set as the maximum flow in that link, the link cost is set to 0, and the channel loss coefficient (slope of linear segment 1 in Fig. 20) is specified under the **Channel Loss** tab (Fig. 23).

For certain problems where it is desirable to include pumping costs, MODSIM allows direct entry of unit costs in the **Link Properties** form for any link in the network. Negative costs can be entered to represent benefits, such as from low head hydropower production, since MODSIM solves a minimum cost network flow optimization problem. If these costs are nonlinear functions of flow in the link, the *multilink* method described previously for nonlinear channel loss functions can be similarly applied. In this case, the cost functions must be convex (i.e., with increasing slope) and the benefit functions

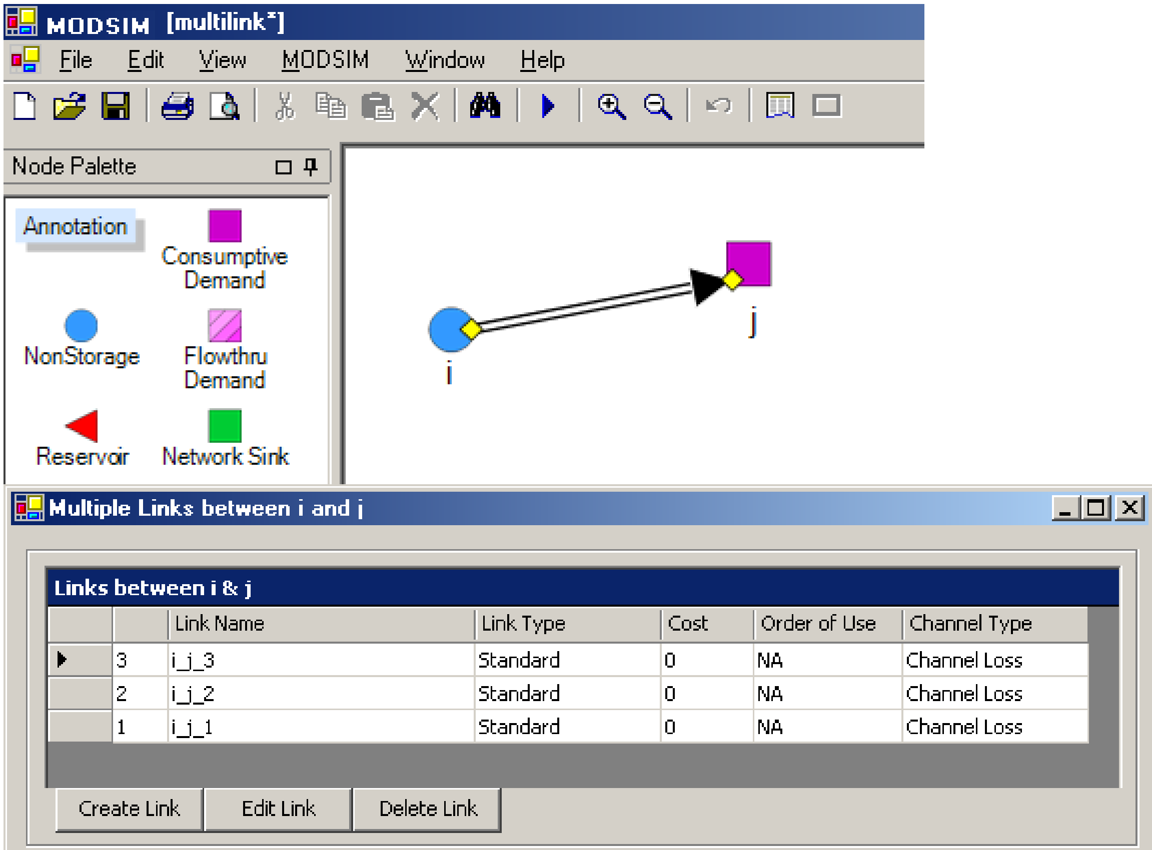


Fig. 21. Creation and editing of multiple links.

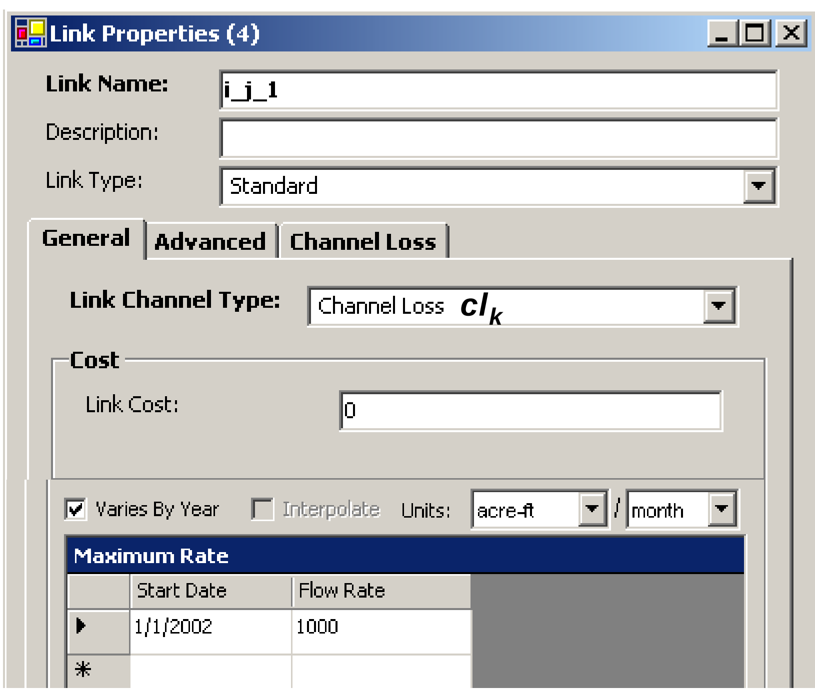


Fig. 22. Specification of link capacity and link cost for link 1 in multilink..

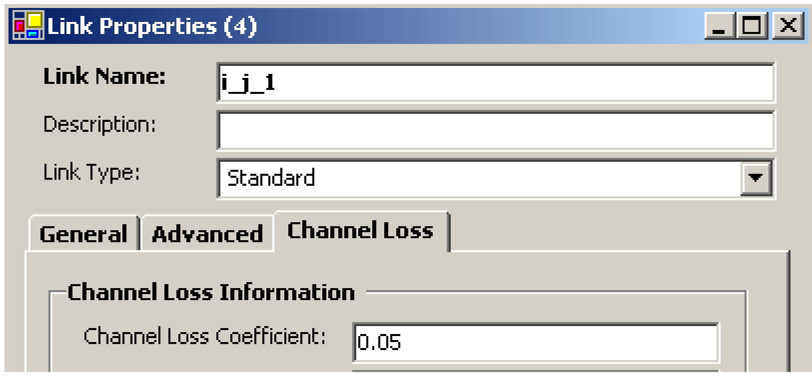


Fig. 23. Specification of channel loss coefficient for link 1 in multilink.

(represented as negative costs) must be concave (i.e., decreasing slopes in order to insure correct minimum cost solutions by the network flow optimization algorithm. Costs or penalties (positive or negative) can be directly assigned to any link by the user to discourage or encourage, respectively, flow in that particular link according to predefined operational criteria. It must be remembered, however, that if water right priorities are included in the network, then any link costs introduced by the user must be set at small relative values that will not disrupt the distribution of flows according to the water right priorities.

D. Channel Routing

For simulation of daily streamflow, it may be necessary to consider channel routing. This is accomplished in MODSIM by designating a network link as a *routing link*. Inflow to this link is distributed over time in accordance with routing coefficients calculated by MODSIM using the Muskingum formula. Alternatively, the user may directly input any desired routing coefficients and lagging factors. An iterative process similar to calculation of flow-through demands is employed, except that returns to the channel are distributed according to the routing coefficients over the current and future time steps. Assuming that the flow entering routing link k during time step t is q_{kt}, then routed outflow from link k is:

$$q'_{kt} = c_0 q_{kt} + c_1 q_{k,t-1} + c_2 q_{k,t-2} + \ldots \tag{19}$$

where q'_{kt} is the ordinate of the outflow hydrograph at time t; $q_{j,t-\tau}$ is the ordinate of the inflow hydrograph at time $t-\tau$ for $\tau = 0,1,\ldots$; and $c_0, c_1, \ldots$ are routing coefficients. The routing coefficients may be calculated by MODSIM based on the Muskingum routing equations by selecting *Model Generated* under **MODSIM** > **Network Settings** > **Lag Factor Type**, as shown in Fig. 24. Selecting the *User Generated* option and specifying the *Maximum Number of Lags* assumes that users will enter the routing coefficients directly.

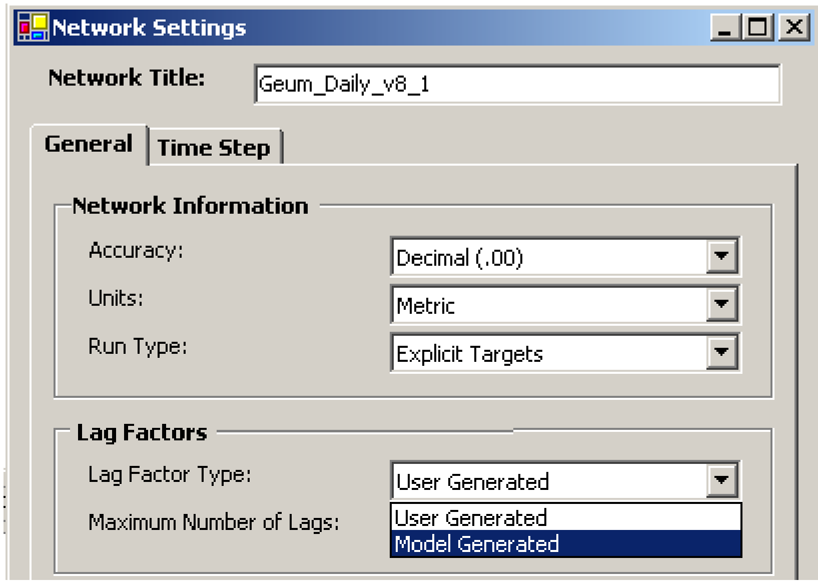


Fig. 24. Selection of *User Generated* lag factors or *Model Generated* (Muskingum method).

The Muskingum routing coefficients are calculated by MODSIM as follows:

$$c_0 = \frac{(\Delta t - 2XK)}{(2K(1-X)+\Delta t)} \tag{20}$$

$$c' = \frac{((2K(1-X)+\Delta t)-2\Delta t)}{(2K(1-X)+\Delta t)} \tag{21}$$

$$c_1 = c_0 \cdot c' + \frac{(\Delta t + 2XK)}{(2K(1-X)+\Delta t)} \tag{23}$$

$$c_i = c_{i-1} \cdot cc \quad \text{for} \;\; i \geq 2 \tag{24}$$

where users enter weighting factor X as a dimensionless number usually between 0 and 0.5 representing the relative influence of the inflow in determining the prism storage volume in reach k. Parameter K is in units of days (or fraction of a day) in this case, representing travel time through the reach, and Δt is generally set to 1 for daily time increments. To avoid negative coefficients, the Muskingum parameter K should be within the following limits:

$$\frac{\Delta t}{(2\cdot(1-X))} < K \leq \frac{\Delta t}{2X} \tag{25}$$

An iterative process is employed in MODSIM for routing daily flows, as illustrated in Fig. 25, where the superscript ℓ is an iteration counter. At iteration $\ell = 0$, an initial MODSIM solution is found that temporarily ignores flow routing. This results in flow $q_{kt}^{(0)}$ in

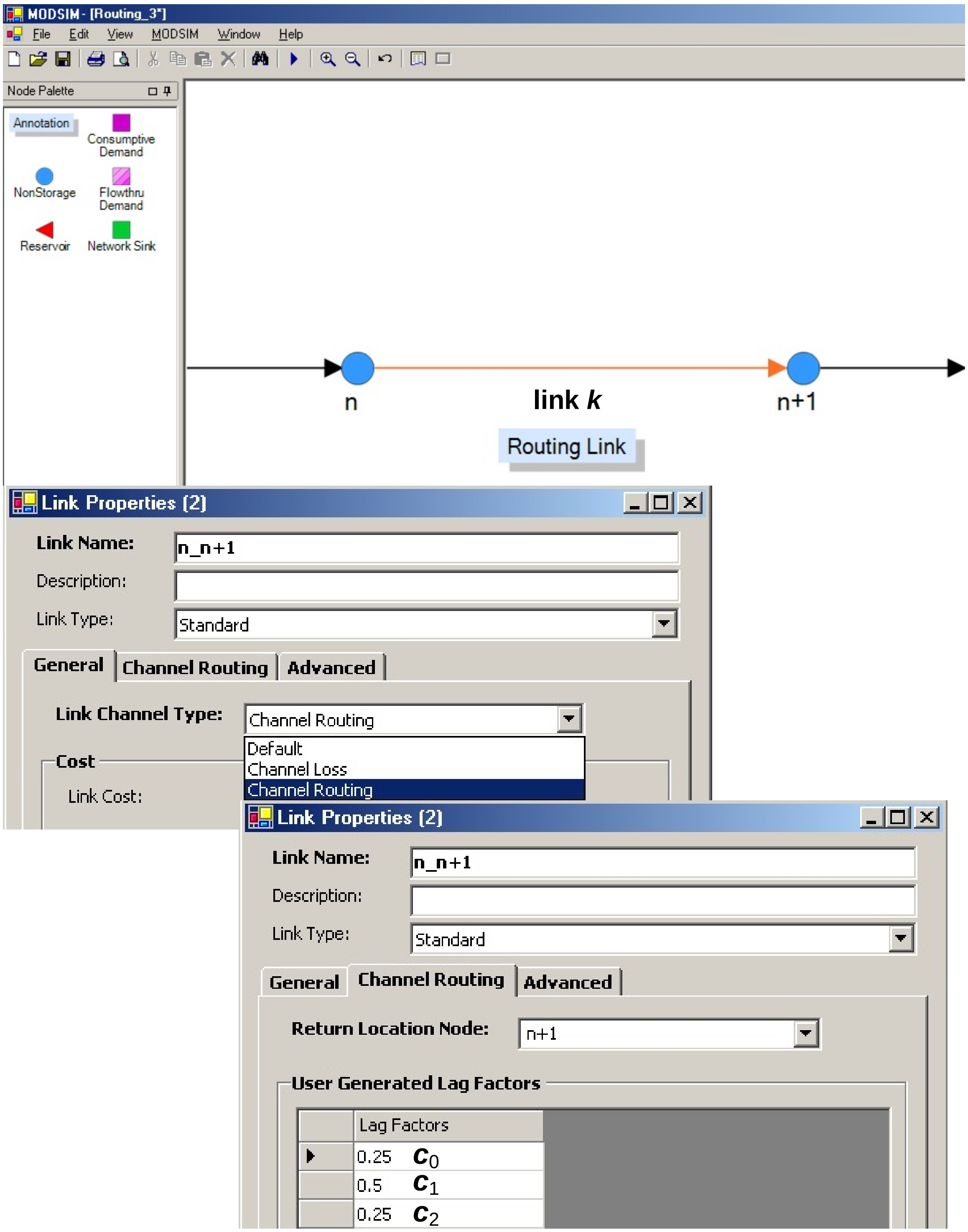


Fig. 25. Specification of Channel Routing link and associated parameters.

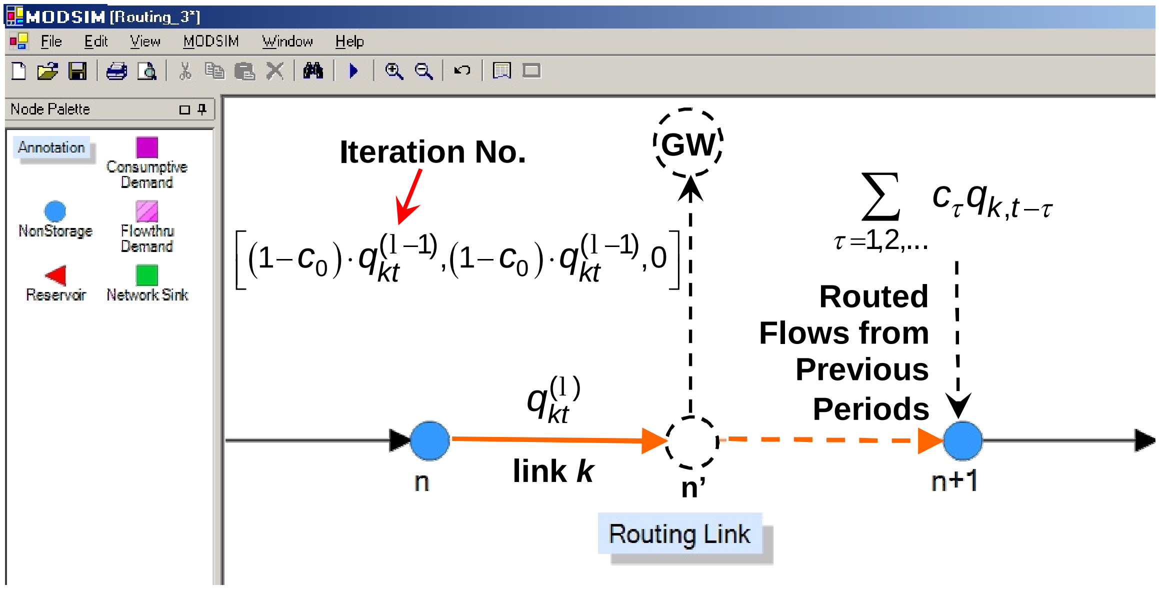
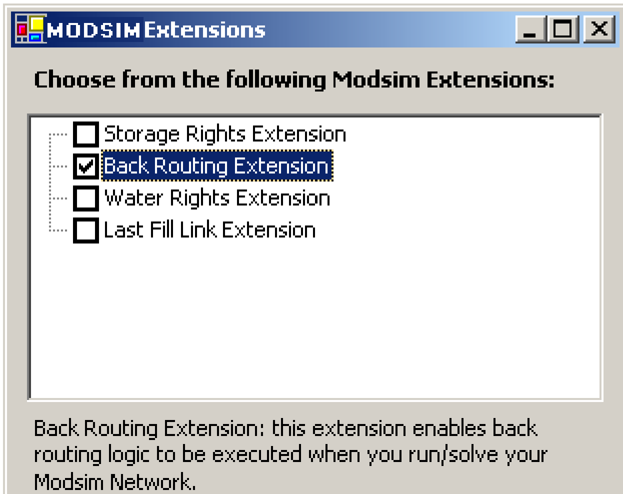


Fig. 26. Successive approximations procedure for channel routing.

routing link k during current time t. As shown in Fig. 26, an artificial link is then created that removes the portion of this flow appearing downstream in future time steps, with the remaining flow passing downstream representing the portion of the routed link flow occurring in the current time step t. In the background (not seen on the

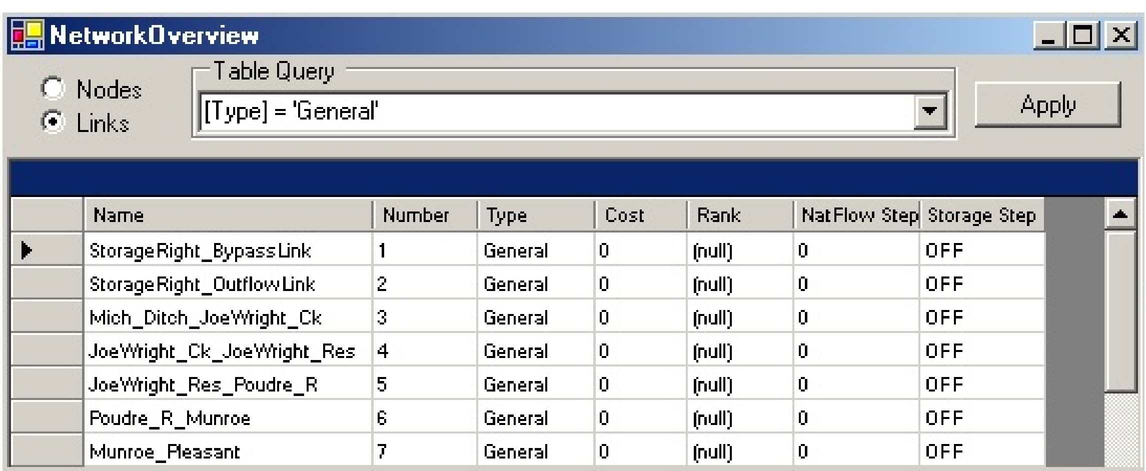
MODSIM GUI palette), the MODSIM interface creates a new artificial node that divides the routing link k into two parts. The upstream portion represents flow in the routing link *prior to* occurrence of routing. The downstream portion of the divided link carries routed flows occurring in the current time step t only, with routed flows appearing at time step t due to flows in link k occurring *prior to* time step t placed back into a *return* node which is the original terminal node for routing link k. Current estimates of future routed flows are specified as bounds on the artificial link conveying these flows to the artificial groundwater node (**GW**), where these routed flows are returned back to node n+1 at future time steps. Notice that the link parameters on the artificial link to node **GW** specify exactly the routed flows defined by the upper and lower bounds that must be removed from the river reach during time step t and subsequently added back downstream at future time steps. This iterative process continues until some iteration ℓ where $q_{kt}^{(l)} \cong q_{kt}^{(l-1)}$ within a user specified convergence tolerance. A restriction on routing in MODSIM is that a routing link cannot be included in a loop or a bifurcation structure where diverted flows bypass the routing link and are directly returned downstream.

The normal streamflow routing procedure employed in MODSIM will produce correct solutions as long as there is sufficient water to satisfy all demands, whether they are of low or high priority. Difficulties arise when there is insufficient water available to meet all demands, and priorities exist on allocation of water. Under water shortage conditions and priorities on demands, routing time steps longer than one day can cause downstream demands to *pull* water from upstream reservoirs, although they do not receive this water immediately. This can cause unnecessary releases of additional water from upstream reservoirs that are in excess of downstream demands. A *backrouting* methodology has been implemented in MODSIM to overcome the problem of excessive reservoir drawdown associated with longer routing periods. The backrouting extension is selected by clicking the **Backrouting Extension** checkbox under **MODSIM** > **Extensions**. Details on the backrouting procedure, along with simple examples, can be found in Appendix C.



E. Editing Link Properties

As with the ability to edit node priorities using the **Network Overview** form under **MODSIM > Cost Analysis**, certain link properties can also be edited in the same form by selecting the radio button next to *Links*. The link *Cost* entries can be directly edited in this form, as well as some additional properties related to water rights and storage accounts to be discussed subsequently. Similar *Table Queries* can also be made in order to sort the links to be displayed according to user-specified criteria.



VII. STREAM-AQUIFER MODELING COMPONENTS

A. Stream-Aquifer Interactions

The stream-aquifer module within MODSIM performs dynamic calculation of reservoir seepage, irrigation infiltration, pumping, channel losses, return flows, and river depletion due to pumping (Fig. 27). Stream-aquifer return/depletion flows are simulated using response coefficients calculated using the one dimensional equations developed by Glover (1977). These are similar to groundwater response coefficients estimated from the stream depletion factor (sdf) method of Jenkins (1968). Alternatively, as described in Fredericks, et al. (1998), response coefficients can be generated from three-dimensional finite difference groundwater models such as MODFLOW (Harbaugh and McDonald, 1996) and read into MODSIM from external data files. This allows response coefficients to be calculated based on spatially distributed aquifer characteristics and complex boundary conditions.

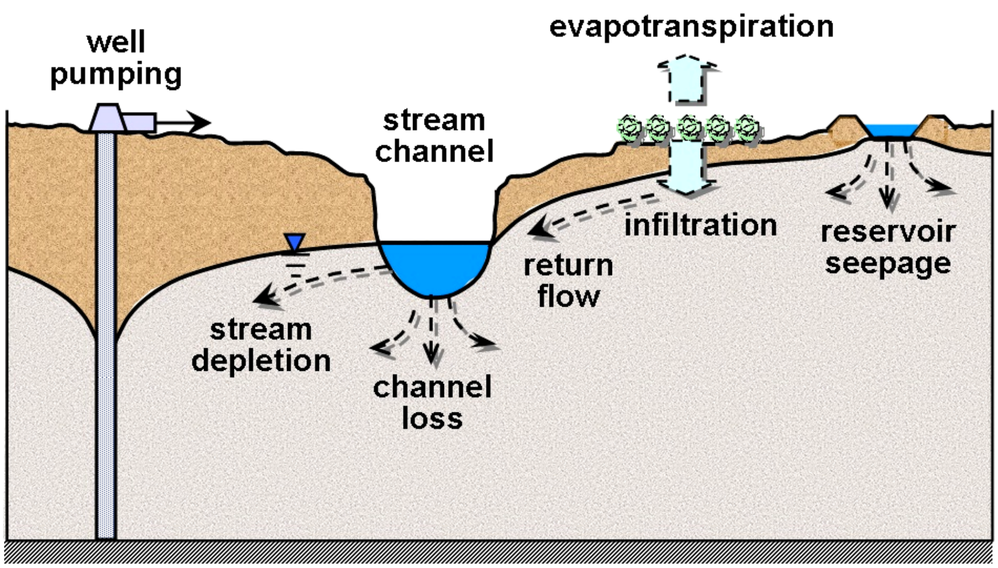


Fig. 27. Stream-aquifer interaction components in MODSIM

B. Irrigation Return Flow Calculations

The infiltration or aquifer recharge rate during time interval *t* is $I_{it} = f_{it} \cdot q_{it}$, where q_{it} is the total water delivery to demand node *i* and f_{it} is the infiltration fraction entered into the **Demand Node Properties** form under the **Groundwater** tab . For any irrigation demand node *i* and current time period *t*, the total return flow IRF_{it} from the current and previous time periods due to groundwater recharge is calculated using linear superposition:

$$IRF_{it} = \sum_{\tau=t'}^{t} I_{i\tau} \cdot \delta_{i,t-\tau+1} \; ; \; \text{for } t' = \max(1, t - n_{\max}) \qquad (26)$$

where $n_{\max}$ is the *Maximum Number of Lags,* entered into **MODSIM > Network Settings > General** for selection of *Model Generated* as **Lag Factor Type**; $\delta_{i\tau}$ is the response or discrete kernel coefficient defined for node *i* and time lag τ. If **Lag Factor Type** is selected as *User Generated,* then *Maximum Number of Lags* is based on the number nonzero lag coefficients entered by the user.

Details on calculation of the response coefficients $\delta_{i\tau}$ for irrigation return flows in MODSIM are given in Appendix B. Calculations are based on the parallel drain analogy originally proposed by Maasland (1959) and extended to stream-aquifer systems in Glover (1977). The semi-infinite aquifer is assumed to be homogeneous, with groundwater recharge uniformly distributed over the average width of the irrigated area measured from the centroid of the adjacent river channel at the return flow node. Return flows may also be spatially distributed over several return flow nodes based on user specified distribution fractions. These return flow calculations can also be applied to municipal demand areas as long as the assumption of uniform groundwater recharge over the area is considered a reasonable approximation.

The artificial groundwater node **GW** in Fig. 4 is treated as a reservoir with a large initial storage representing a phreatic or unconfined aquifer with direct connection to the surface water system. MODSIM is not applicable to confined aquifers, although approximate simulations can be obtained by representing the confined aquifer as a reservoir. Mining of groundwater is not allowed in MODSIM, and it is assumed that groundwater withdrawals are restricted by safe-yield requirements. It is therefore assumed in MODSIM that steady-state groundwater levels are relatively stable and that transient changes in average groundwater depth to bedrock are less than 10%, which avoids the need for directly calculating groundwater heads in MODSIM. This maintains reasonable computational error bounds in the solution of the linearized Boussinesq equation, where it is assumed that aquifer transmissivity is constant and does not vary with head.

As illustrated in Fig. 28, the bounds on the artificial infiltration and artificial return flow links are adjusted iteratively as follows:

(1) At initial iteration $\ell = 0$, artificial infiltration link lower and upper bounds are first set to 0, and artificial return flow link bounds are set equal to return flows occurring from previous period activities. That is, for artificial infiltration link [*i*,**GW**], the parameters are: [0, 0, 0] and for artificial return flow link [**GW**, *j*], the parameters are: $\left[IRF_{it}^{(0)}, IRF_{it}^{(0)}, 0 \right]$, where

$$IRF_{it}^{(0)} = \sum_{\tau=t'}^{t-1} I_{i\tau} \cdot \delta_{i,t-\tau+1} \; ; \; \text{for } t' = \max(1, t - n_{\max})$$

with the MODSIM network solution resulting in flows $q_{it}^{(0)}$.

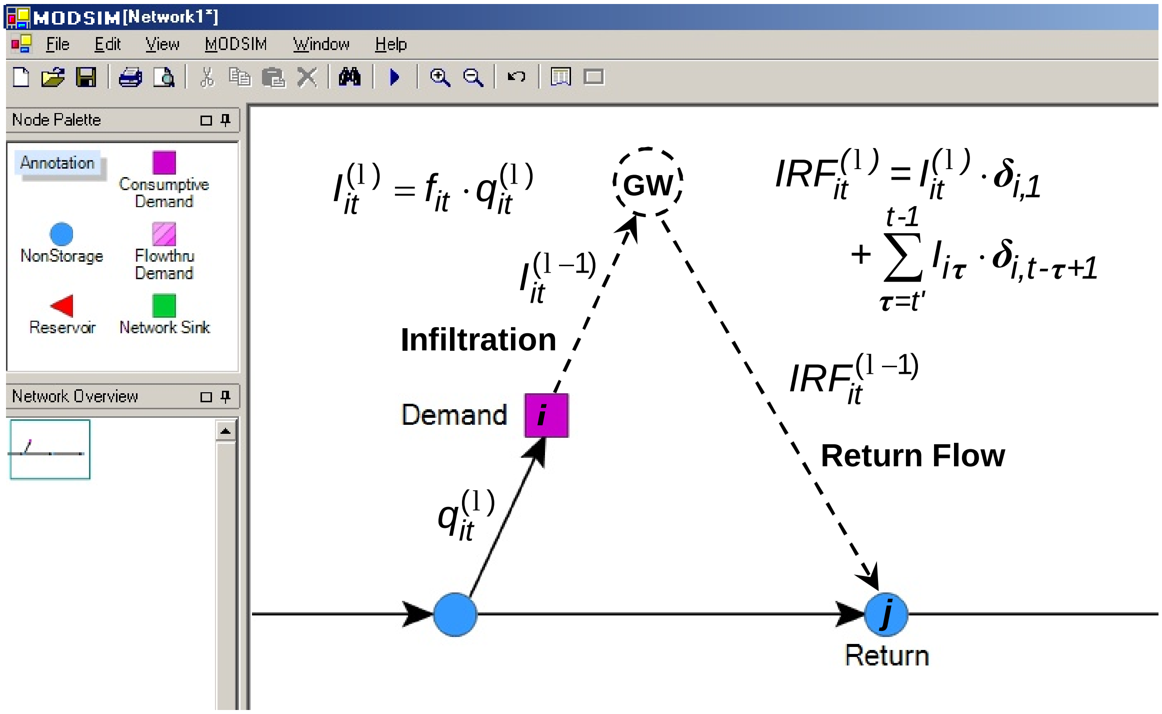


Fig. 28. Successive approximations procedure for return flow calculations

(2) At iteration $\ell > 0$, arc parameters for artificial infiltration link [i,**GW**] are: $\left[I_{it}^{(l)}, I_{it}^{(l)}, 0 \right]$ where $I_{it}^{(l)} = f_{it} \cdot q_{it}^{(l-1)}$; for artificial return flow link [**GW**,j], the parameters are: $\left[IRF_{it}^{(l)}, IRF_{it}^{(l)}, 0 \right]$, where

$$IRF_{it}^{(l)} = I_{it}^{(l)} \cdot \delta_{i,1} + \sum_{\tau=t'}^{t-1} I_{i\tau} \cdot \delta_{i,t-\tau+1} \;;\; \text{for } t' = \max\left(1, t - n_{\max}\right)$$

with the MODSIM network solution resulting in flows $q_{it}^{(l)}$.

(3) If $q_{it}^{(l)} \cong q_{it}^{(l-1)}$ within a desired error, then convergence has occurred; otherwise, $\ell \leftarrow \ell + 1$ and return to Step (2).

As shown in Appendix B, the response coefficients $\delta_{i\tau}$ calculated using the Maasland (1959) parallel drain analogy require specification of aquifer transmissivity T_i, storage coefficient S_i, and average distance to return nodes a_i, assumed to correspond to the average width of the irrigated area.

Fig. 29 displays the input of the stream-aquifer parameters into the **Groundwater** tab of the **Demand Node Properties** form, along with the desired fractional distribution of return flows to one or more specified return flow nodes.

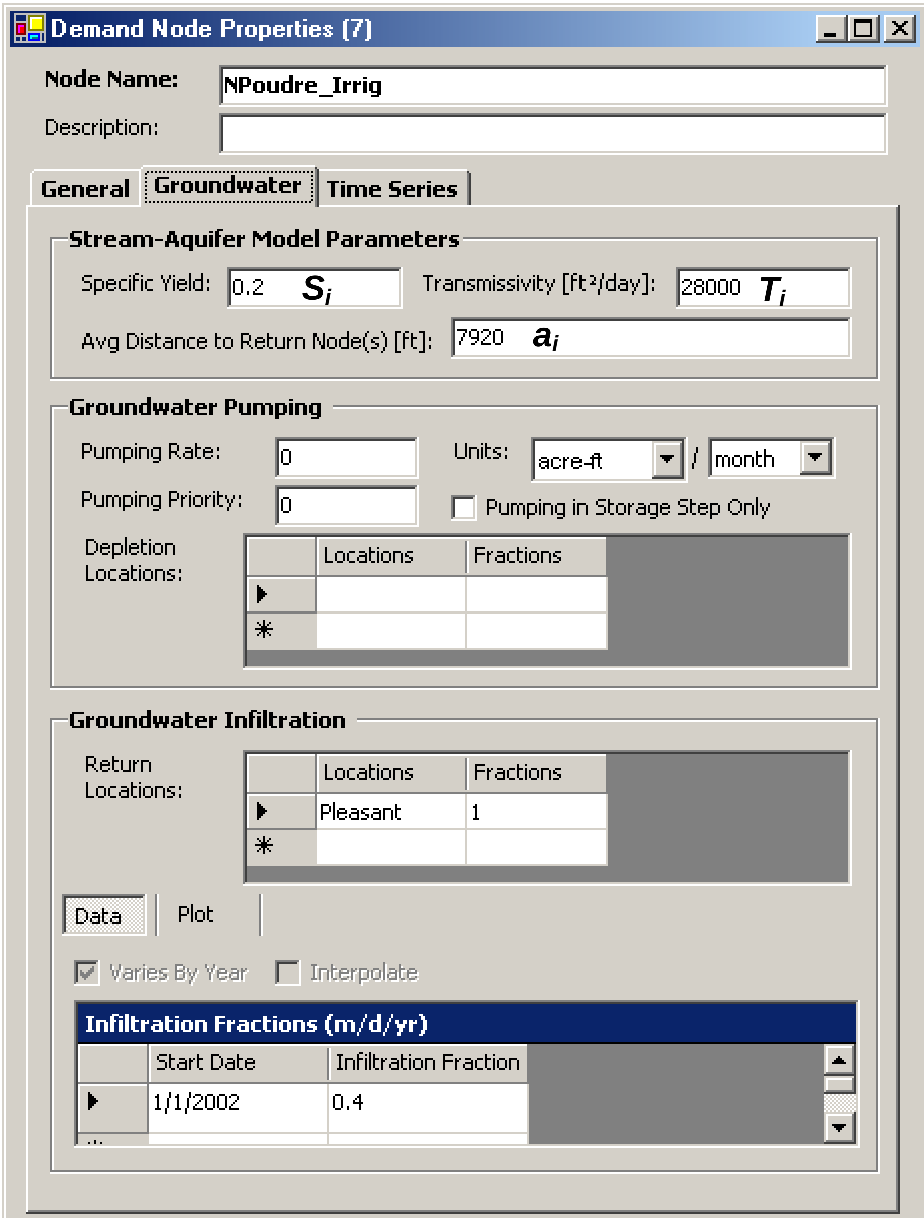


Fig. 29. Specification of stream-aquifer model parameters and return flow locations.

Selection of *User Generated* as **Lag Factor Type** under **MODSIM > Network Settings > General** allows users to manually input response coefficients or import them from a database containing response coefficients generated from a 3-dimensional numerical finite difference groundwater model such as MODFLOW (Harbaugh and McDonald, 1996), as seen in Fig. 30. Some example response coefficients generated from the MODFLOW model are shown in Fig. 31 for varying aquifer properties and distances from the return flow nodes for the Nile River Delta aquifer (Salem and Labadie, 1995).

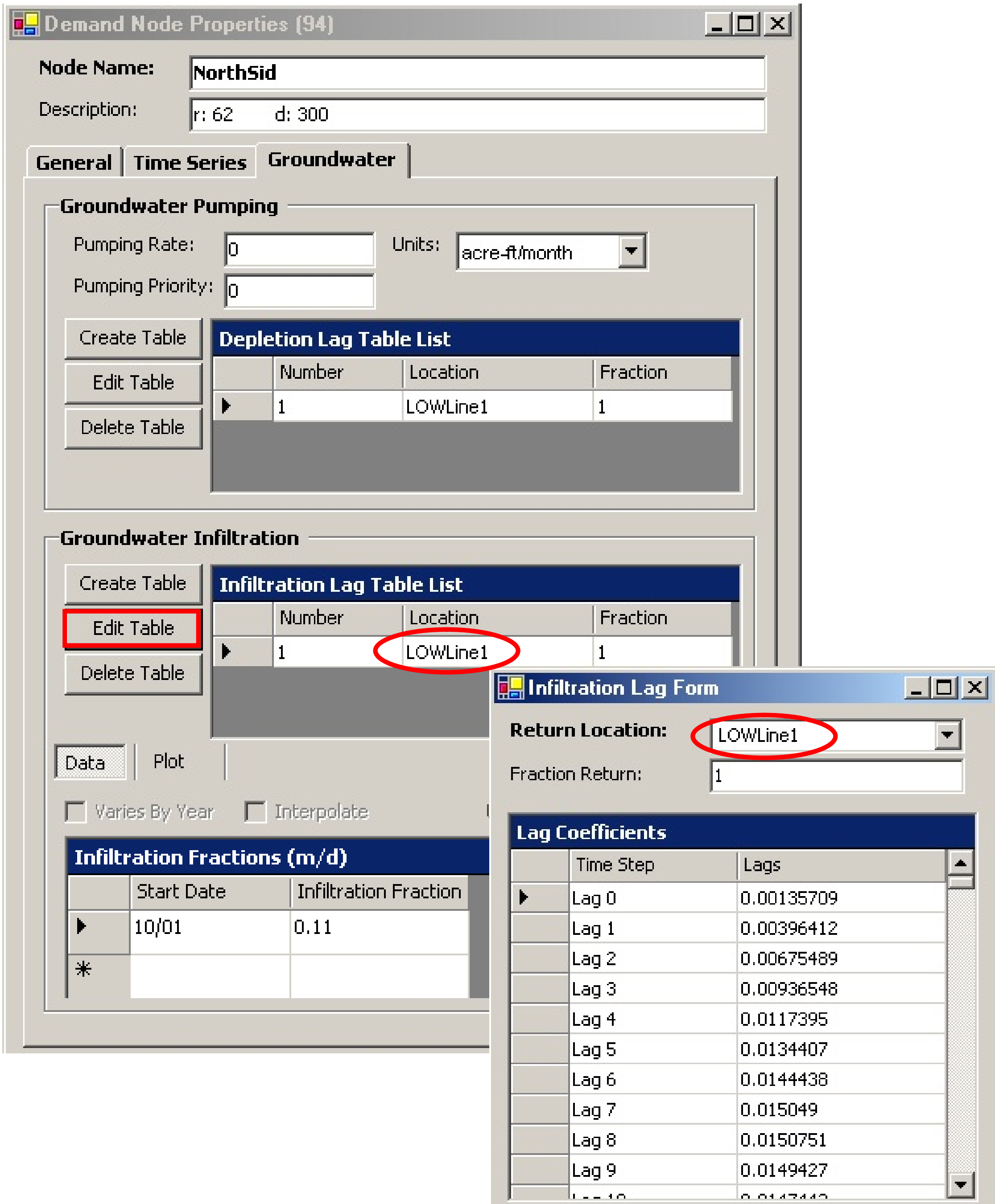


Fig. 30. Import of response coefficients calculated from 3-dimensional finite difference groundwater model.

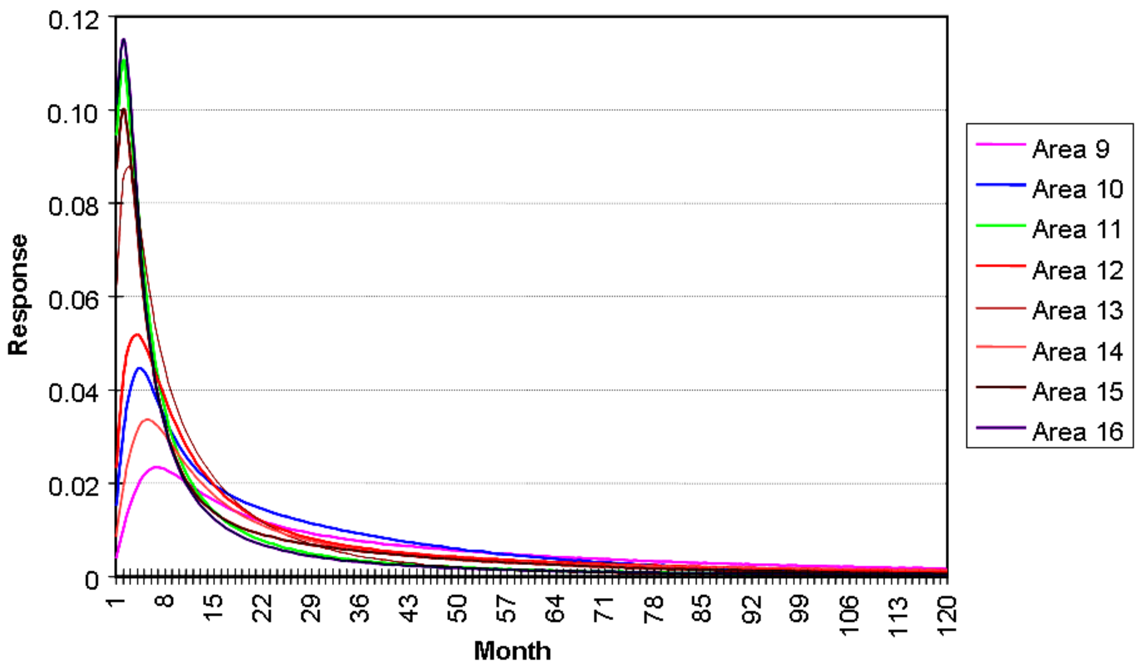


Fig. 31. Example response coefficient plots for areas of varying aquifer and distance from stream.

Stream Depletion Factor Method (sdf). Glover (1977) proposed the following equation for relating the stream depletion rate q to aquifer pumping rate Q to time t:

$$\frac{q}{Q} = 1 - erf\left(\frac{a}{\sqrt{4tT/S}}\right) \tag{27}$$

Jenkins (1968) solved the Glover equation graphically by developing dimensionless curves and tables to compute the rate and volume of stream depletion by wells. Under ideal conditions, the *stream depletion factor* (*sdf*) represents the time in days where the volume of stream depletion is 28% of the volume pumped during time t, and can be expressed as:

$$sdf = \frac{a^2 S}{T} \tag{28}$$

where a is perpendicular distance from the pumped well to the stream (L); S is specific yield of the aquifer (dimensionless); and T is transmissivity ($L^2 t^{-1}$). In terms of *sdf*, the Glover equation can be written as:

$$\frac{q}{Q} = 1 - erf\left(\sqrt{\frac{sdf}{4t}}\right) \tag{29}$$

In a complex system, the value of *sdf* can represent integrated effects of irregular impermeable boundaries, stream meanders, aquifer properties, areal variation, distance from the stream, and hydraulic connection between stream and aquifer. The *sdf* is intended to be a calibrated parameter determined from numerical modeling of stream-aquifer systems. The basic assumption is that *sdf* generated response functions can have shapes similar to those calculated from 3-dimensional numerical finite difference groundwater models, such as developed by Hurr and Burns (1980) and Warner et al., (1986) for regional stream-aquifer system modeling. An example *sdf* map developed by Jenkins and Taylor (1974) is shown in Fig. 32.

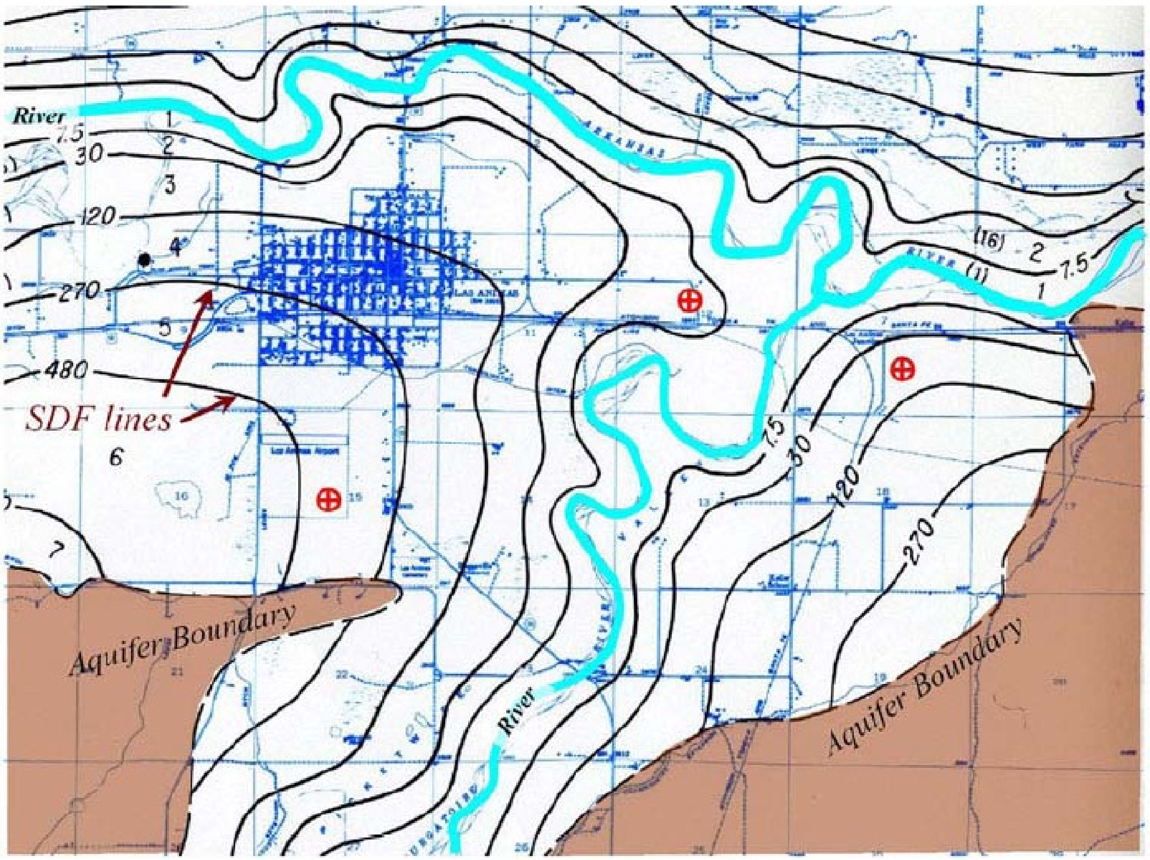


Fig. 32. Example *sdf* map for the Arkansas River Valley, Colorado (Jenkins and Taylor, 1974).

The same Glover equation can be used to represent stream accretion rate *q* to aquifer reacharge rate *Q* over time *t*. The *sdf* concept can also be applied to the Maasland parallel drain analogy for calculating irrigation return flows, although it can no longer be interpreted as exactly representing the time in days where the volume of stream accretion is 28% of the volume of recharge under ideal conditions. Fig. 33 shows how *sdf* values can be entered into the **Groundwater** tab of the **Demand Node Properties** form in place of explicit specification of aquifer parameters. The *Specific Yield* entry is now interpreted as *sdf* in this case, with values of 1 entered for *Transmissivity* and *Ave. Distance to Return Node(s)*, which results in *sdf* values being correctly incorporated into the return flow calculations.

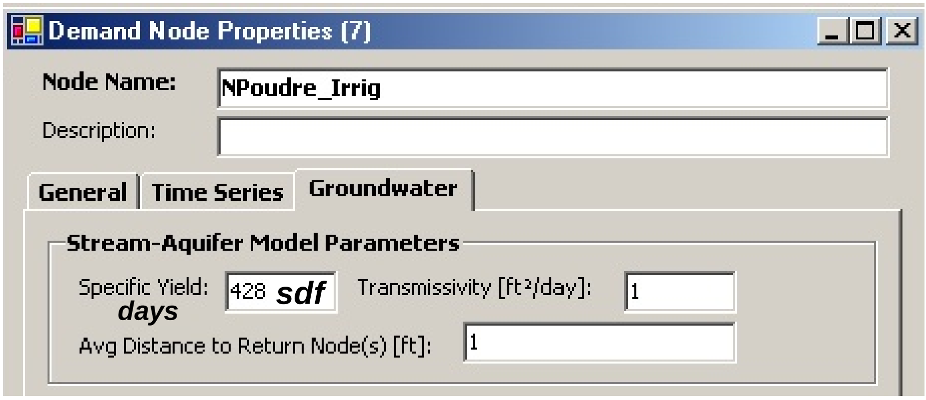


Fig. 33. Input of *sdf* in place of explicit values of the explicit stream-aquifer model parameters.

Since computations in MODSIM are sequentially carried out period by period, the current period stream-aquifer interactions are contingent upon stresses during previous periods (i.e., both aquifer recharge and groundwater withdrawals), it is recommended to run MODSIM for an initial N periods for start-up or initialization purposes, such that after N periods, the model output can be trusted to properly account for past history. Specification of N is left to the user.

C. Return Flow from Canal Seepage

Seepage from a canal or a stream is assumed to correspond to a line source of recharge water in MODSIM. McWhorter and Sunada (1977) developed the governing equations for a one-dimensional line source in an infinite aquifer, as described in detail in Appendix B. This solution is for a continuous application of a line source. After termination of the source, the residual effect still contributes flow to the stream. The residual is taken into account by assuming an imaginary pumping source at the same location and initiating pumpage at the same rate as the recharge source from the time recharge terminates. The volume ratio at any time after recharge ceases is the difference between the volume ratio obtained if recharge had continued and the volume ratio obtained from pumping of the imaginary pumping source. For a discrete time interval, if the applied line source volume equals one, the volume ratio is in essence the unit response of line source or canal seepage.

Let $\phi_{k\tau}$ represent the unit response of canal seepage in link k for time lag τ. Then, for canal link k, the total return flow CRF_{kt} from canal seepage C_{kt} during time interval t is:

$$CRF_{kt} = \sum_{\tau=t'}^{t} C_{k\tau} \cdot \phi_{k,t-\tau+1} \;;\; \text{for } t' = \max\left(1, t - n_{\max}\right) \tag{27}$$

where $n_{\max}$ is the *Maximum Number of Lags*. In MODSIM, bounds on the artificial canal seepage or channel loss link and artificial return flow link (Fig. 34) are adjusted iteratively as follows:

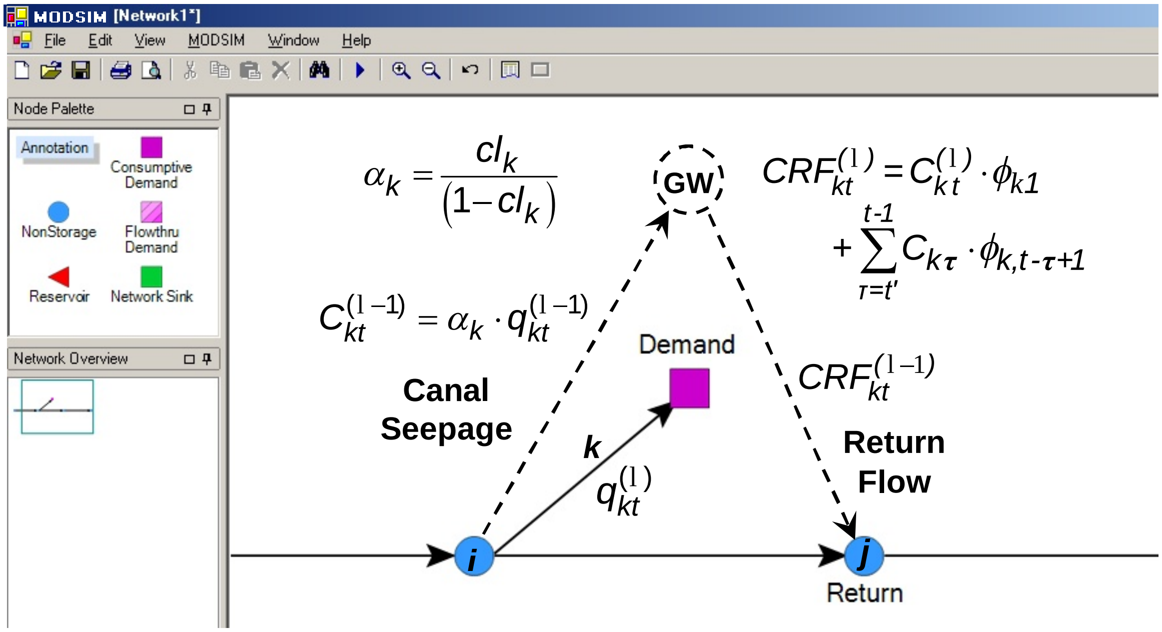


Fig. 34. Successive approximations procedure for calculating return flow from canal seepage.

(1) At initial iteration ℓ = 0, artificial canal seepage link lower and upper bounds are first set to 0, and artificial return flow link bounds are set equal to return flows occurring from previous period activities. That is, for artificial canal seepage link [i,**GW**], the parameters are: [0, 0, 0] and for artificial return flow link [**GW**, j], the parameters are: $\left[CRF_{kt}^{(0)}, CRF_{kt}^{(0)}, 0\right]$, where

$$CRF_{kt}^{(0)} = \sum_{\tau=t'}^{t-1} C_{k\tau} \cdot \delta_{i,t-\tau+1} \ ; \ \text{for } t' = \max\left(1, t - n_{\max}\right)$$

with the MODSIM network solution resulting in flows $q_{kt}^{(0)}$.

(2) At iteration ℓ > 0, arc parameters for artificial canal seepage link [i,**GW**] are: $\left[C_{kt}^{(\ell)}, C_{kt}^{(\ell)}, 0\right]$ where $C_{kt}^{(\ell)} = \alpha \cdot q_{kt}^{(\ell-1)}$; for artificial return flow link [**GW**,j], the parameters are: $\left[CRF_{kt}^{(\ell)}, CRF_{kt}^{(\ell)}, 0\right]$, where

$$CRF_{kt}^{(\ell)} = C_{kt}^{(\ell)} \cdot \phi_{i,1} + \sum_{\tau=t'}^{t-1} C_{k\tau} \cdot \phi_{i,t-\tau+1} \ ; \ \text{for } t' = \max\left(1, t - n_{\max}\right)$$

with the MODSIM network solution resulting in flows $q_{kt}^{(\ell)}$.

(3) If $q_{kt}^{(\ell)} \cong q_{kt}^{(\ell-1)}$ within a desired error, then convergence has occurred; otherwise, $\ell \leftarrow \ell+1$ and return to Step (2).

As shown in Appendix B, the response coefficients $\phi_{k\tau}$ calculated using the line source solution require specification of aquifer transmissivity T_k, storage coefficient S_k, and the perpendicular distance a_k from canal link k and the return node. Fig. 35 displays the input of these parameters into the **Channel Loss** tab of the **Link Properties** form.

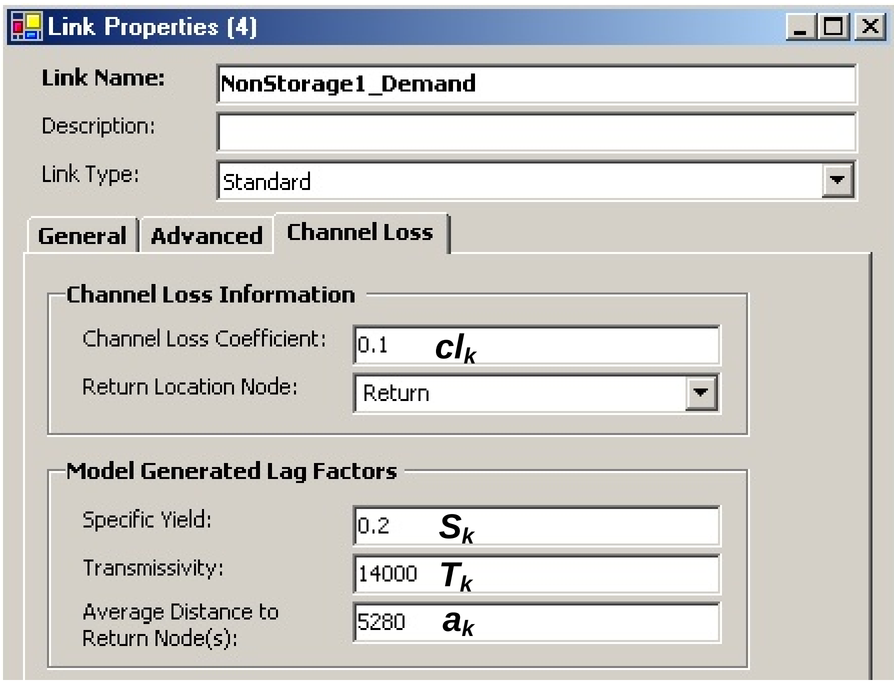


Fig. 35. Specification of stream-aquifer model parameters and return flow locations for canal seepage link *k*.

As with irrigation return flows, Selection of *User Generated* as **Lag Factor Type** under **MODSIM** > **Network Settings** > **General** allows users to manually input response coefficients for return flows from canal seepage or import them from a database containing response coefficients generated from a 3-dimensional numerical groundwater model.

D. Return Flow from Reservoir Seepage

Return flow from reservoir seepage is defined as a point source application. The impact on the stream corresponds to the effect of a recharge well, which has the same absolute flow magnitude as a pumping well, but with the flow direction reversed. As described in Appendix B, this solution turns out to be the same as a line source solution used for calculating return flow from canal seepage (Glover, 1977). There is little error in assuming reservoir seepage as a point source, as long as the reservoir surface area is small in comparison with the area of the subsystem containing it.

Reservoir seepage RS_{it} is defined as a point source application for storage node i, time period t. Therefore, $C_{k\tau}$ is replaced with $RS_{i\tau}$ in Eq. 27, with the resulting return flow defined as RRF_{it}:

$$RRF_{it} = \sum_{\tau=t'}^{t} RS_{i\tau} \cdot \phi_{i,t-\tau+1} \;\; ; \;\; \text{for } t' = \max\left(1, t - n_{\max}\right) \qquad (28)$$

As illustrated in Fig. 36, the same successive approximations procedure is applied to calculation of return flows from reservoir seepage as was applied to canal seepage, where S_{it} is the known reservoir storage at the beginning of period t and $S_{i,t+1}^{(\ell)}$ is end-of-period storage calculated at iteration ℓ.

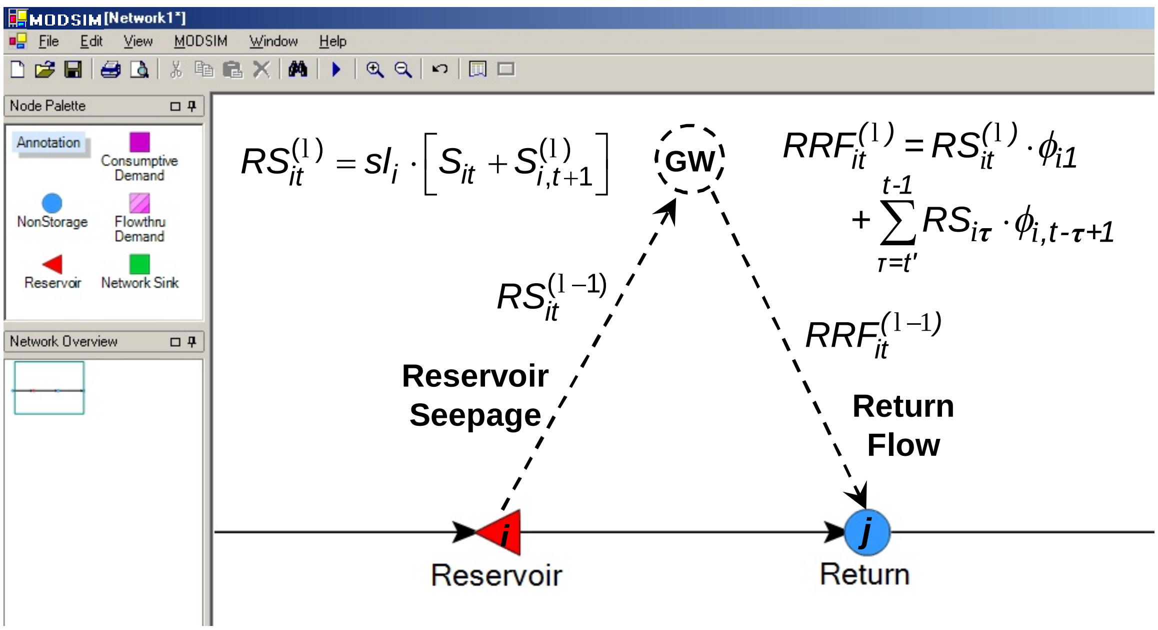


Fig. 36. Successive approximations procedure for calculating return flow from reservoir seepage.

E. Stream Depletion from Groundwater Pumping

The same approach used for calculating return flows is also applied to calculation of stream depletion PSD_{it} due to pumping:

$$PSD_{it} = \sum_{\tau=t'}^{t} G_{i\tau} \cdot \alpha_{i,t-\tau+1} \;\; ; \;\; \text{for } t' = \max\left(1, t - n_{\max}\right) \qquad (29)$$

where $G_{i\tau}$ groundwater withdrawal and response coefficients $\alpha_{i,k-\tau+1}$ are based on the same principles described above for calculating the return flow response coefficients. As with groundwater recharge, it is idealized that pumping withdrawals are uniformly distributed in a well field over the application area, rather than attempting to model individual wells. In MODSIM, groundwater pumping is assumed to provide only a supplemental water supply to satisfy demands, where all available surface water supplies are first fully exploited. Of course, there may be some demands that are only capable of receiving groundwater supplies. As shown in Fig. 37, maximum well field *Pumping Rate* P_{cap} is entered into the **Groundwater** tab of the **Demand Node Properties** form, along with either specification of *Stream-Aquifer Model Parameters* or import of response coefficients calculated from external models such as MODFLOW. The value of P_{cap} entered into the form should not exceed the *safe yield* of the aquifer since MODSIM is not designed for simulating groundwater operations requiring mining of the aquifer storage. *Pumping Priority* $PCOST_i$ entered into the **Groundwater** tab is used to assign the cost to the artificial groundwater pumping link [**GW**, *i*] according to:

$$c_{\mathbf{GW},i} = -\left(50000 - 10 \cdot PCOST_i\right) \tag{30}$$

where $PCOST_i$ is a ranking number generally greater than 5000 such that Eq. 30 calculates a positive cost associated with pumping. This insures that all natural flow links conveying surface water to demand node *i*, which are generally assigned a small negative cost by MODSIM, will have priority over groundwater pumping. However, if $PCOST_i$ is set too high such that the calculated pumping costs exceed the benefits (i.e., negative cost) associated with demand *i* as calculated using Eq. 17, then groundwater pumping will not occur. In this case, the cost of pumping is considered to exceed the cost of shortages to demand *i*. For networks with storage right ownerships, clicking the checkbox next to Pumping in Storage Step Only guarantees that all surface water deliveries will be made before groundwater is pumped for supplemental use.

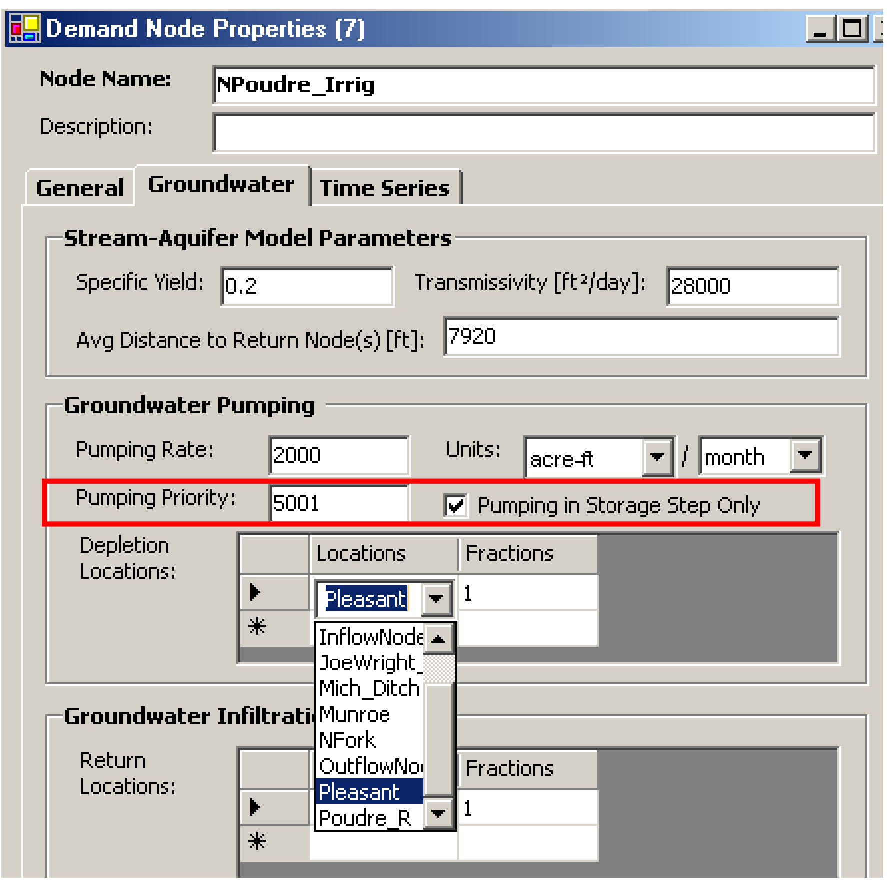


Fig. 37. Groundwater pumping capacity, pumping priority and depletion location(s).

As with the calculation of return flows from groundwater recharge, stream depletion factors (*sdf*) can be entered in place of the *Stream Aquifer Parameters* in the **Groundwater** tab of the **Demand Node Properties** form.

As illustrated in Fig. 38, the calculation of streamflow depletions due to groundwater withdrawals from the connected aquifer follows a similar iterative procedure as required for calculating streamflow accretions from groundwater recharge. Streamflow depletions are calculated based on actual pumpage from the previous iterations, with convergence occurring when successive streamflow depletion calculations differ by an acceptable error tolerance.

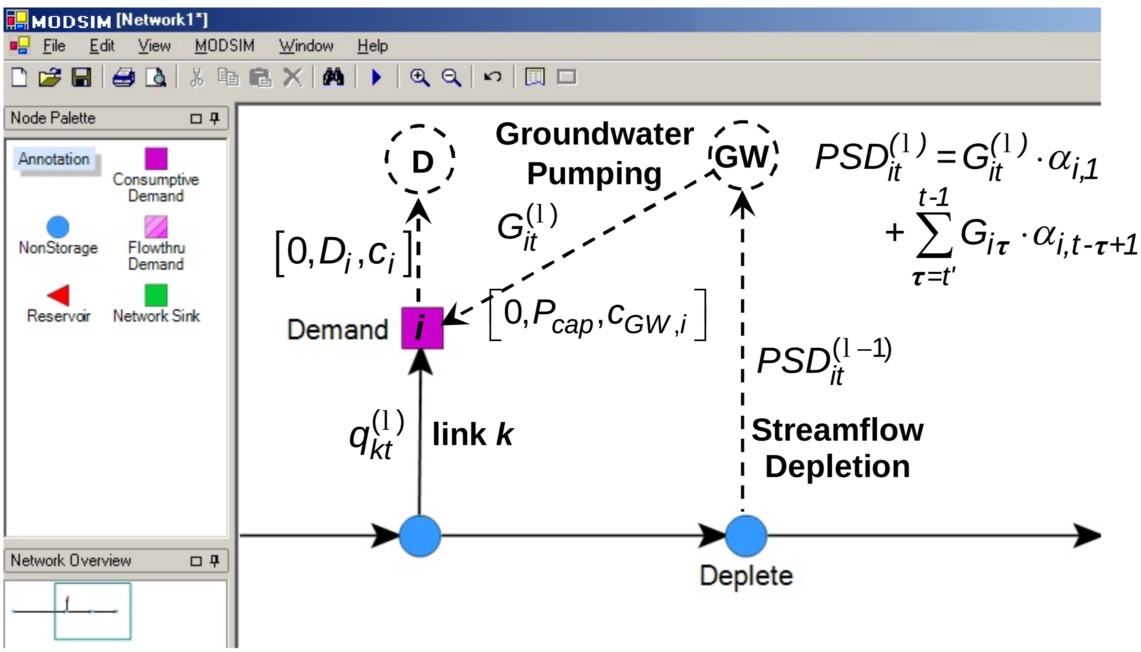


Fig. 38. Successive approximations procedure for calculating streamflow depletions from groundwater pumping.

Since network computations are sequentially carried out period by period in MODSIM, stream-aquifer interactions are contingent upon the time-lagged impact of groundwater recharge and withdrawal operations prior to the starting period for the MODSIM simulation. Therefore, it is recommended to run MODSIM for an initial period of N time intervals for start-up or initialization purposes, such that after N periods, the model calculations can be trusted to properly account for the past history. Specification of an appropriate time lag N for initialization is left to the user. It should be noted that if a demand is receiving water from storage ownership accounts, then a different procedure is required for including groundwater as a supplemental water source for the demand, as discussed in the following section.

VIII. ADVANCED RIVER BASIN ADMINISTRATION FEATURES

A. Water Rights under Prior Appropriation

Doctrine of Prior Appropriation. The large expanse of semi-arid regions in many states of the western U.S. has led to development of a body of water law based on prior appropriation rather than riparian water rights as existing in states with abundant rainfall. The need for this type of water law arose with the development of the West as water supplies for mining and agricultural purposes had to be diverted, in some cases over great distances, to areas nonadjacent to the watercourse. Under prior appropriation, water right amounts are established based on actual beneficial use of the water. The water rights are treated similarly to property rights independently of the land on which the water is applied or lands riparian to the originating water supply such as a river or stream.

Water users appropriating water for beneficial use at the earliest dates have seniority or a higher priority over later water users or *junior* appropriators; hence, the saying "first in time, first in right" has come represent the Doctrine of Prior Appropriation. In many western states, appropriators may obtain a conditional water right *decree* based on the date of appropriation rather than the date of actual use. However, appropriators must show *due diligence* in completing the project for conversion to an absolute water right, but with a priority date that *relates back* to the date of the conditional right. Since appropriative water rights are based on beneficial use, a proven lack of use over a period of time can result in *abandonment* or forfeiture of the water right.

Direct Flow and Storage Rights. Water rights are generally of two types: (i) direct or natural flow rights, and (ii) storage or reservoir accrual rights. A direct flow right is generally defined as a rate of flow, although seasonal water rights based on volume are used in some states. The direct flow right holder has an *entitlement* to continue to take water at the rate specified in the entitlement as long as the water is physically available, the diversion is in priority, and the water is needed for beneficial use. A storage water right is defined as an annual volume that the right holder is entitled to store or accrue to a reservoir account, although limitations may be placed on the maximum daily flow rate allowed for accrual to a storage account. Once the water has accrued to storage, the storage owner may release the water as needed, either for direct use or for the purpose of exchanges and augmentation plans. Storage rights are usually only valid for a single filling of the reservoir per year, although refill rights are possible in some states.

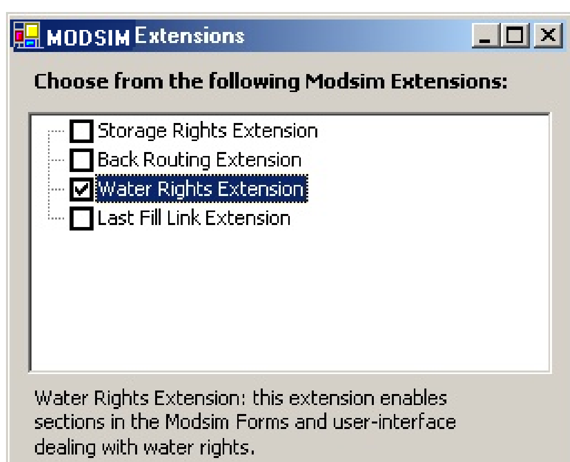
Water Rights for Groundwater Use. The treatment of water rights for groundwater use varies widely among the western states. In some states, tributary groundwater sources, i.e., aquifers hydraulically connected to adjacent waterways, are considered in the same manner as surface water rights. Other states recognize nontributary groundwater, i.e., aquifers not directly connected to natural streams, as a completely different type of water right since pumping from these aquifers has a negligible impact on the surface water system. In at least one of the western states, ownership of nontributary groundwater is tied to ownership of the land overlying the nontributary groundwater source.

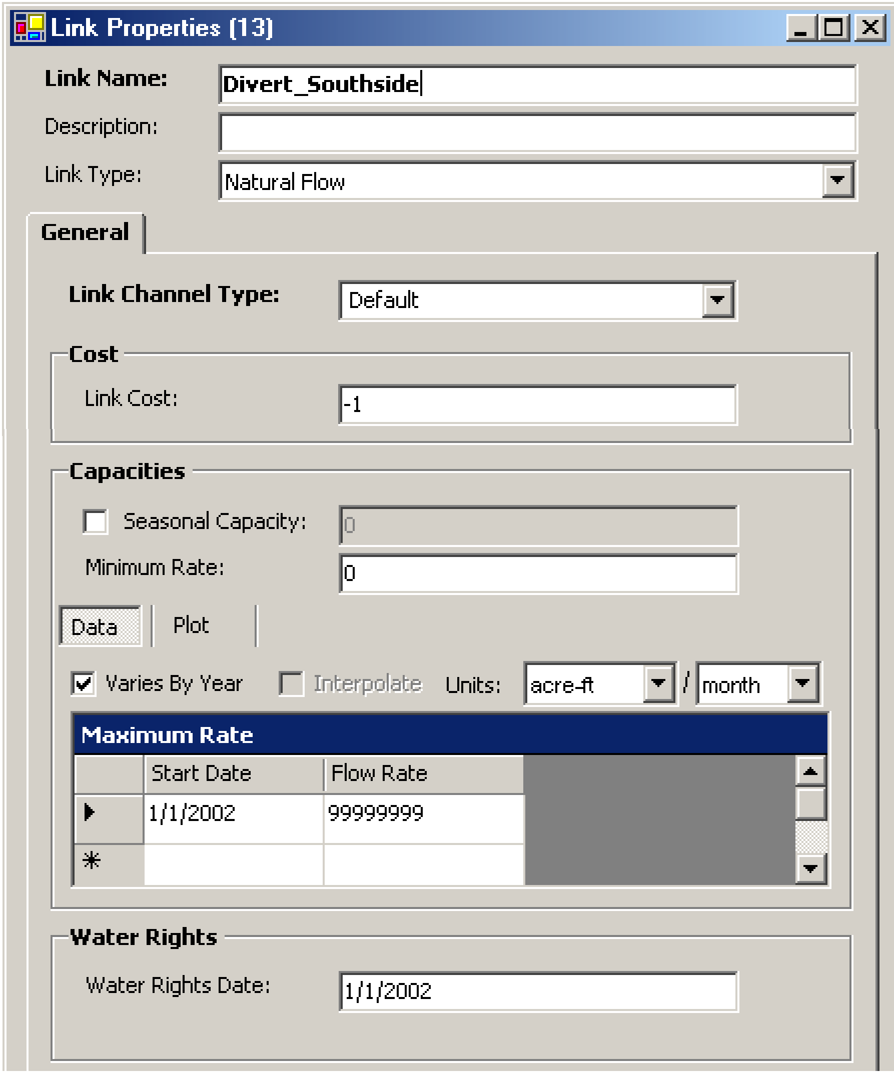
Administration of Water Rights. The administration of water rights within a state is generally charged to the department of water resources in the state government or the designated *state engineer*. The state may be divided into various regions with water rights overseen by a *water commissioner* as a representative of the state to administer water rights in that region. Water rights administration in stream-aquifer systems is a difficult and complex task, requiring modern computing and modeling tools for proper enforcement of the priority system. During drought or low flow conditions, the state engineer or designated administrators may be forced to issue a *call on the river* upstream of a senior water right holder currently being *injured* by diversions from junior appropriators. In this case, upstream water users may be required to temporarily discontinue diversions or groundwater pumping in reverse order of priority until the entitlement for the senior water right holder is available for diversion. Calls on the river must be conducted carefully to insure that only those junior appropriators directly impacting the downstream senior entitlements are curtailed.

Flow Augmentation and Exchange Plans. In order to ameliorate the negative impacts of river calls on junior appropriators, several western states provide for *augmentation* or *exchange* plans whereby junior water right holders are allowed to divert flows or pump groundwater out of priority as long as the resulting river depletions can be replaced in the river such that senior appropriators are not injured. Sources of replacement water may include releases from either on-stream or off-stream reservoirs, senior direct flow water rights no longer used for their original purpose, nontributary ground water, or return flows from groundwater recharge. Approval of a replacement plan permits water users to continue to divert available flows when restrictions would otherwise be required to meet a valid senior call for water.

B. Water Rights Extension

Selection of **Water Rights Extension** in the **MODSIM Extensions** form accessed from **MODSIM > Extensions** results in creation of a new **Link Type** called the *Natural Flow* link. With selection of *Natural Flow* as the link type in the **Link Properties** form (Fig. 39), the link cost is set to a default value of -1 under the **General** tab since MODSIM uses negative costs as designation of a *Natural Flow* link. A new **Water Rights Date** text box is also created, with a default date entered which is easily changed by the user.





Selection of the **Water Rights Extension** also results in creation of a new **Water Right Control** item under the **MODSIM** menu. Clicking the **Water Right Control** menu item opens the **Water Rights – Priorities Extension** form for adding new water rights to the MODSIM network or editing existing rights.

Node Based Water Rights Creation. Clicking the *Add Water Right* button in the **Water Rights – Priorities Extension** form displays the **Water Rights Editor** (Fig. 40). Checking the radio button next to *Node Based* allows users to create a water right as a new link connecting the designated *From Node* with the *To Node*. If a link connecting these two nodes does not currently exist, it is created by the **Water Rights Editor**. Since each water right is represented by a separate link, multiple direct flow or storage water rights are represented as a multilink in the MODSIM GUI. Notice that water right links are not physical links, but rather provide a representation of flow diversion allowed under a particular water right decree. In this example, the water rights are natural flow or direct flow rights since they convey flows to demands. Storage rights for reservoirs are designated as links with a *Seasonal Capacity*, representing the total accumulated delivery in the link over the season (e.g., year) allowed for filling the reservoir. In addition,

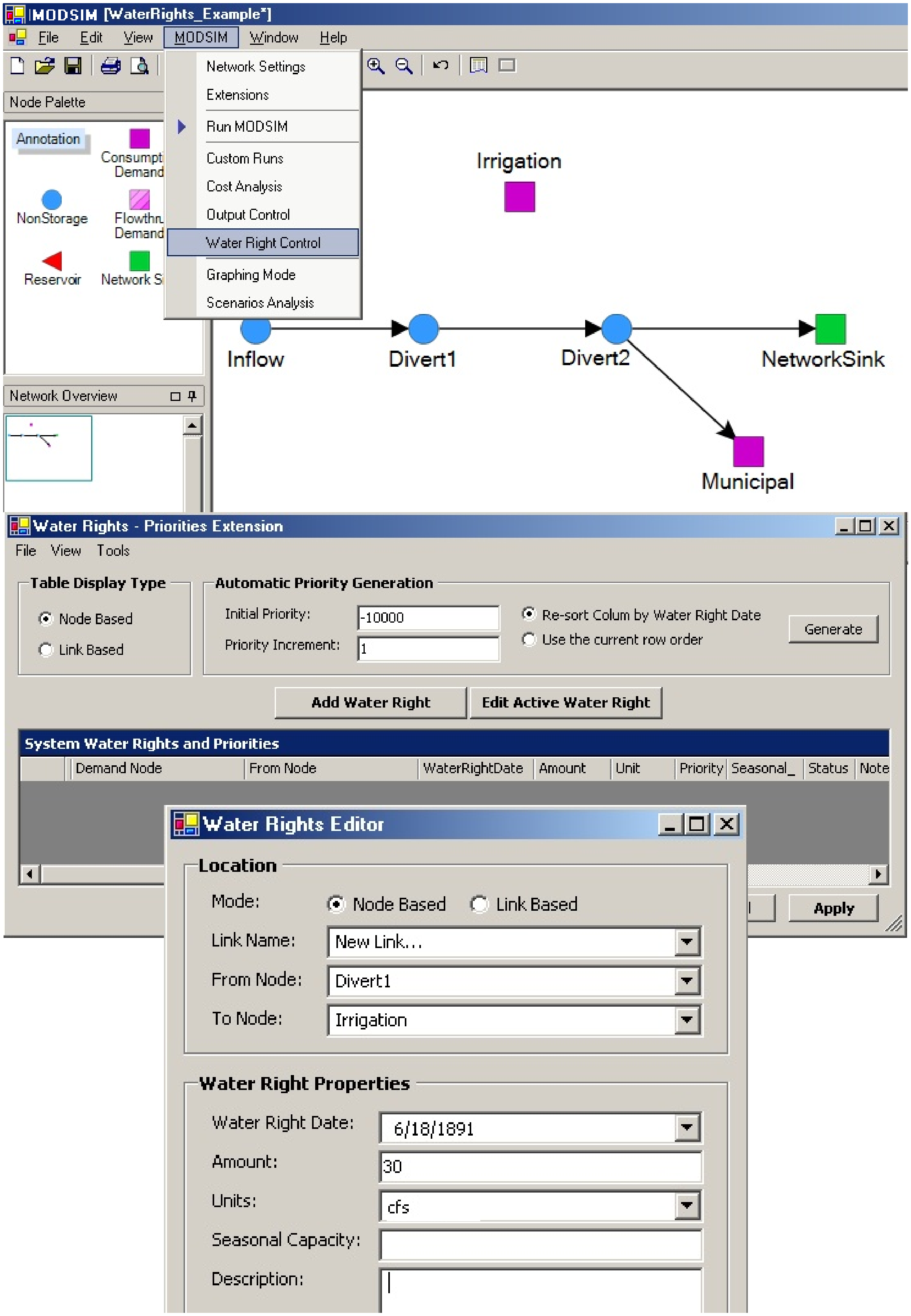
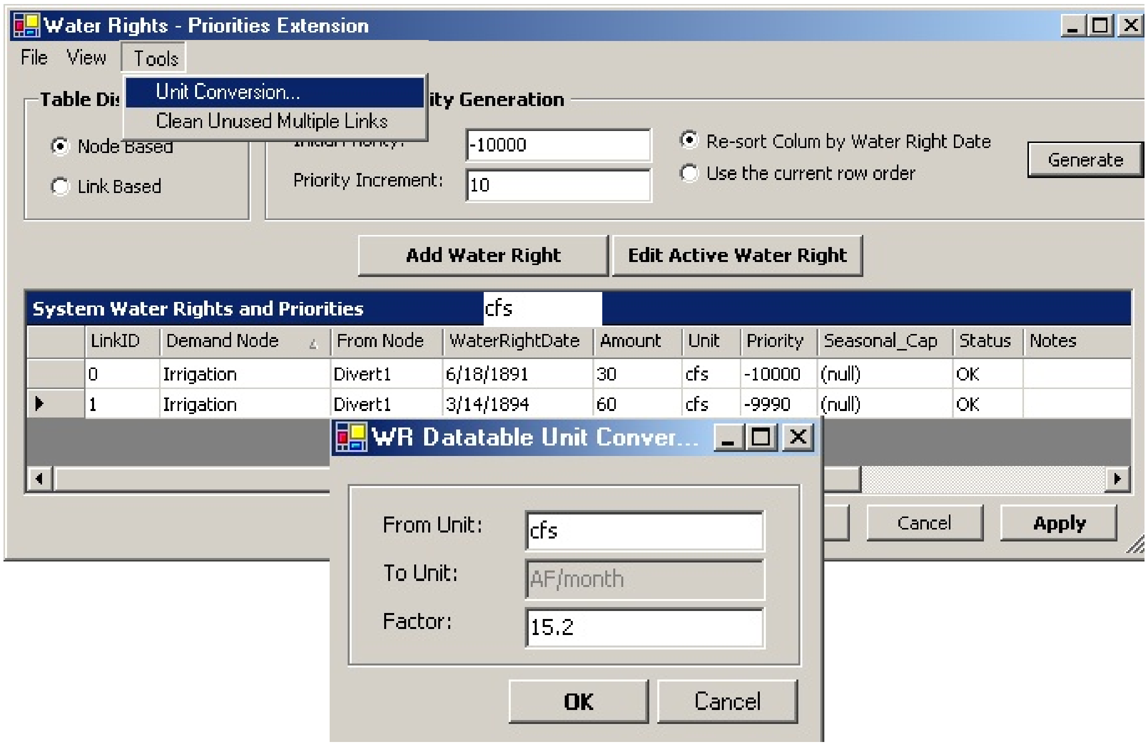


Fig. 40. Display of Water Rights Editor under Water Right Control.

seasonal storage rights may also have associated delivery *Amounts* as maximum flow rates allowed for filling the reservoir in addition to the total seasonal storage right. A *Water Right Date* is specified which is translated into a negative cost on that link by the **Water Rights – Priorities Extension.** The **Add Water Right** button can be clicked again to add additional water rights using the **Water Rights Editor**, which results in display of all the water rights created thus far. Clicking on **Tools > Unit Conversion** displays the **WR Data Table Unit Conversion** form for converting the water right decree units to the specified flow units of the MODSIM network which, for this example network, are ac-ft/month.



A default *Initial Priority* is specified in the **Water Rights – Priorities Extension**, which can be changed by the user. A *Priority Increment* can also be specified whereby clicking the **Generate** button will automatically calculate negative costs for each water rights link as ranked by the *Water Right Date* entered into the **Water Rights Editor**, with higher *negative* costs for water rights with *earlier* decree dates. Again, the absolute values of the negative costs are not significant, but rather their relative magnitudes among all the water right links. The term *Priority* in this form is referring to actual negative costs directly assigned to the water right links, rather than priorities such as reservoir priority $OPRR_i$ as used in Eq. 4 or demand priority $DEMR_i$ in Eq. 17. Clicking **OK** in this form displays the multilink created by the **Water Rights – Priorities Extension** representing the storage rights created for **Reservoir**. The form now shows the water right *Amounts* in the correct units as well as the generated negative costs assigned to the water right links. Clicking **OK** reveals the creation of the multilink defining the two water rights for the Irrigation demand (Fig. 41).

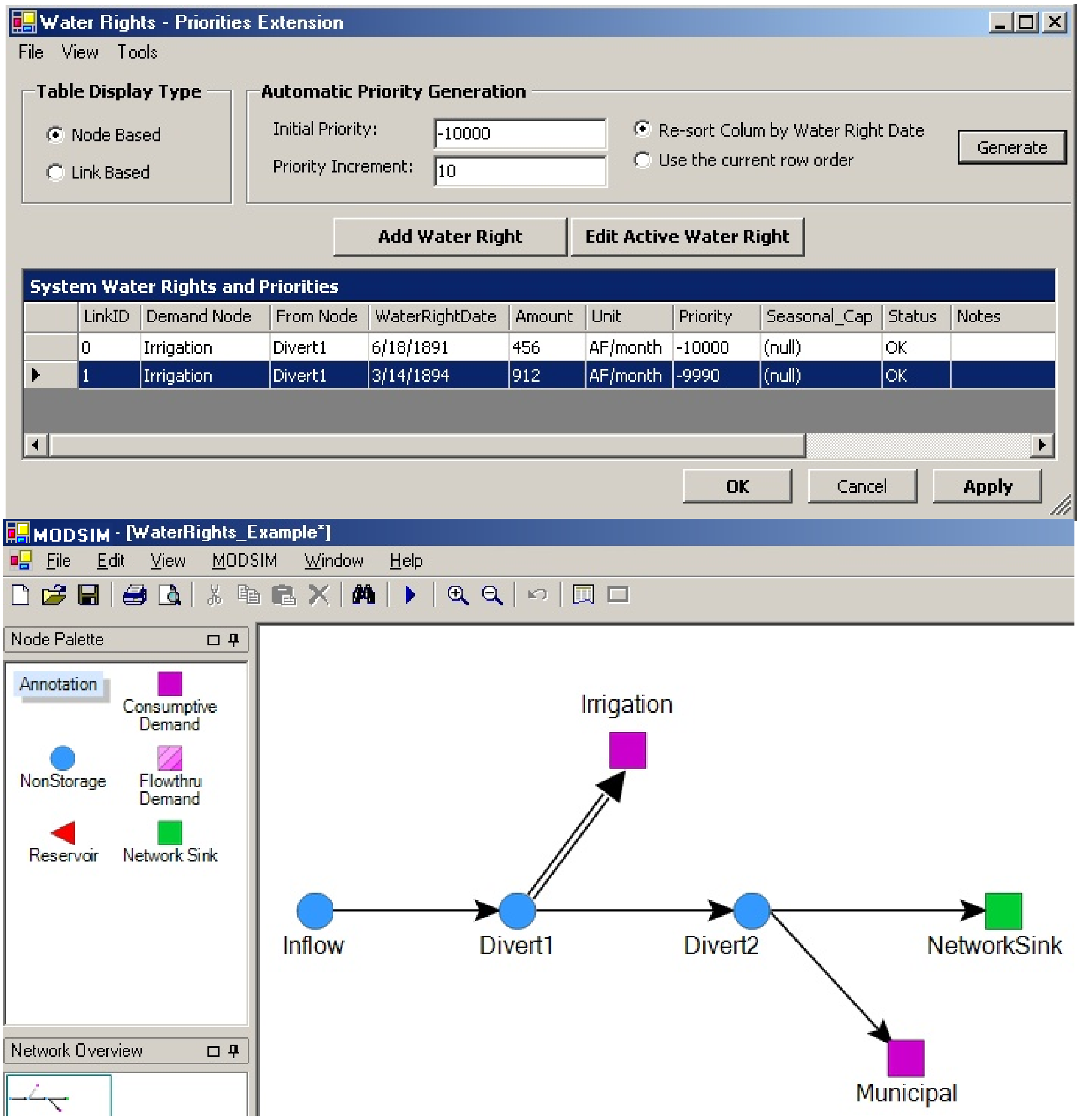
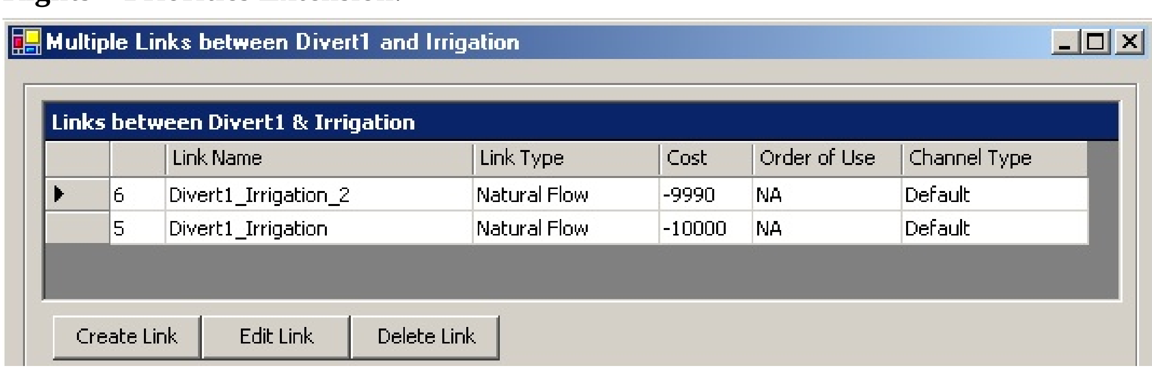
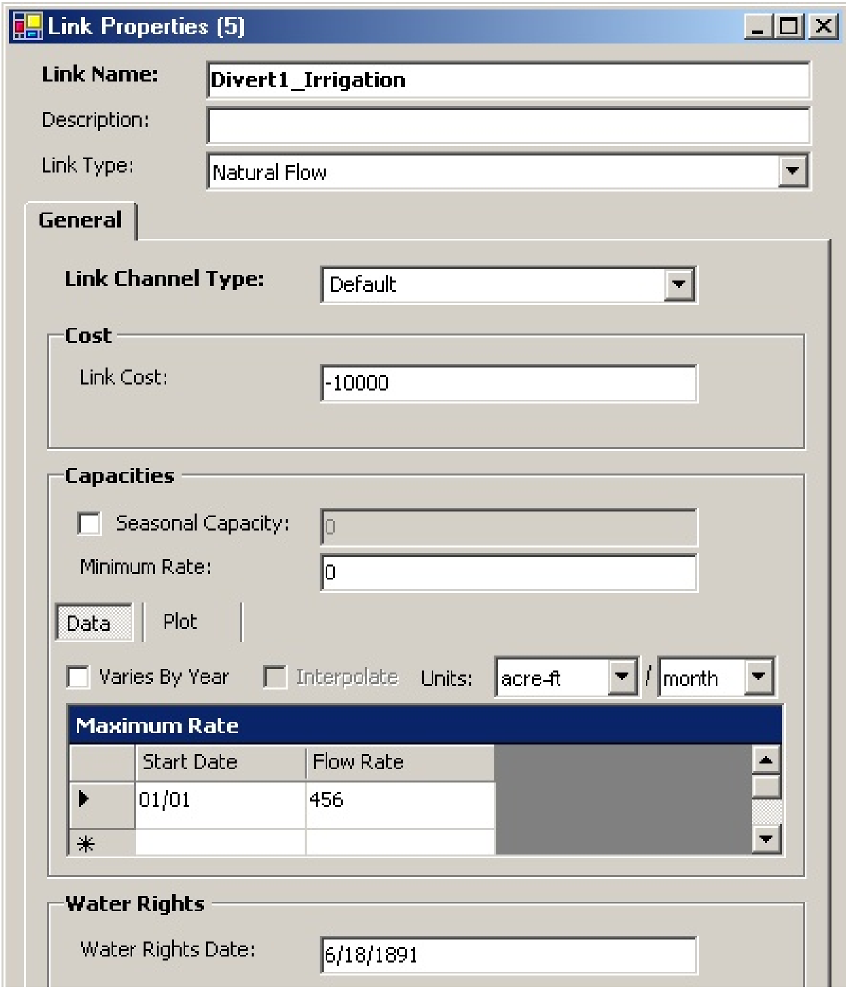


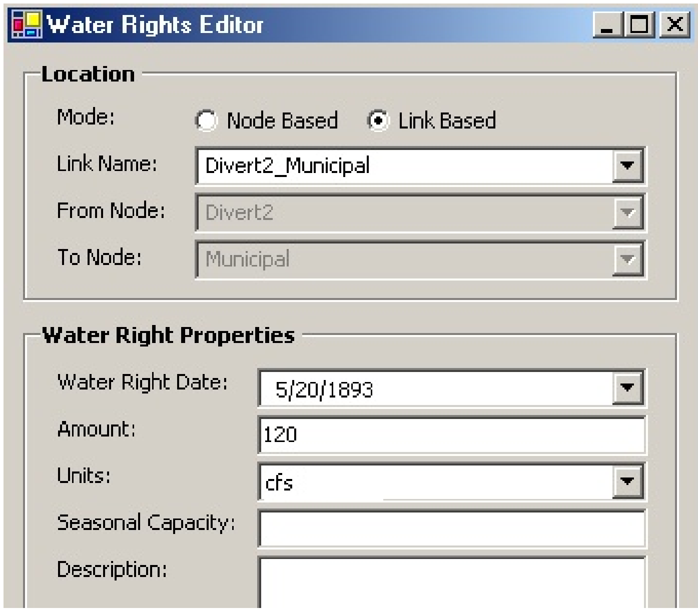
Fig. 41. Automatic creation of multilinks from **Water Rights Control**.

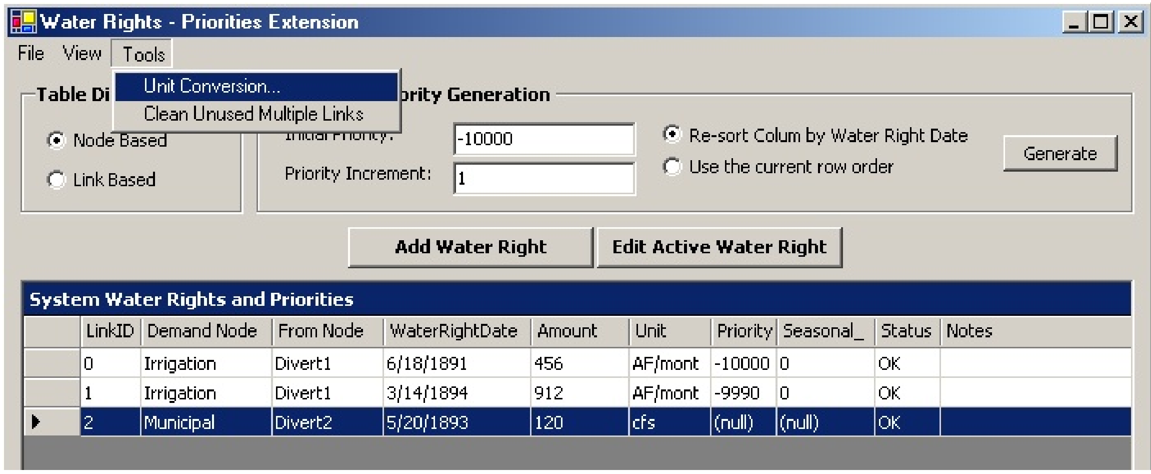
Opening the **Properties** form for the Multilink and clicking **Edit Link** for one of the links shows the correct values for *Link Cost* and *Flow Rate* as generated from the **Water Rights – Priorities Extension**.



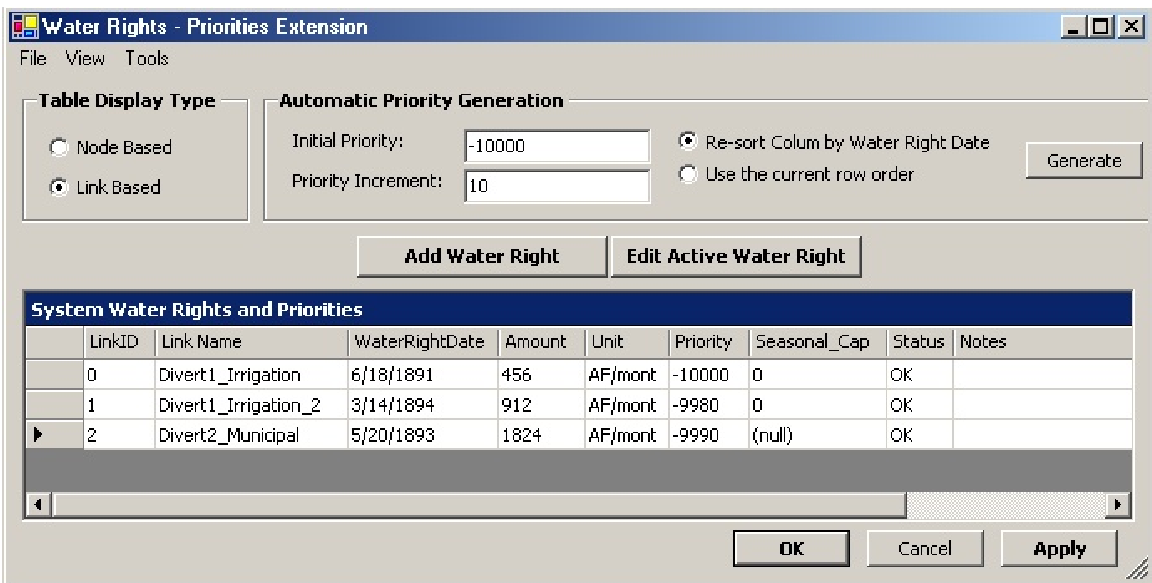


Link Based Water Rights Creation. For assigning water rights to already existing links in a MODSIM network, selecting **MODSIM > Water Right Control** again displays the **Water Rights – Priorities Extension** form, from which the **Add Water Right** button can be clicked as before. The radio button next to *Link Based* is clicked, which allows users to Browse to any existing link in the network and create water rights information for that link. As before, the **Unit Conversion** tool can be applied to the new water rights links.



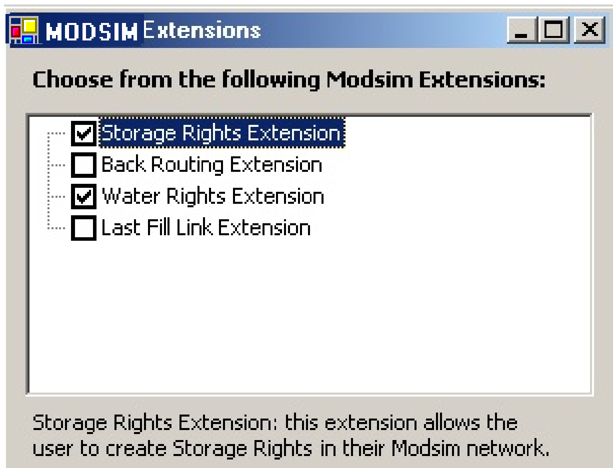


The **Generate** button can again be clicked, resulting in correct ordering of negative costs assigned to all water rights link according to the date of the water right decree.



C. Storage Rights Extension

MODSIM includes advanced administrative features for storage contract arrangements such as accrual rights, storage ownership contracts, water service contracts, and rental pool or water banking. In many areas of the western U.S., development of reservoir storage occurred when the demand for water in summer months exceeded the natural flow of the river. In most cases, senior natural or direct flow rights exhaust available runoff in mid and late summer, resulting in junior or lower priority natural flow rights not being satisfied. When a storage reservoir is constructed, the State assigns storage rights to the reservoir, representing a portion of the reservoir active capacity with a priority date relative to the natural flow rights in the river basin. Contract agreements are implemented that assign a portion of the storage right to a water user (e.g., an irrigation canal or district). Bookkeeping processes account for the distribution of natural flow to the natural flow rights, including the reservoir storage rights. Once water has *accrued* to a storage right in a reservoir, this storage water is no longer distributed based on water rights, but rather is delivered as needed to the contract holders in proportion to their contract amount. The sum of all contracts equals the sum of all storage rights, which cannot exceed the total active capacity of the reservoir.



Storage Contracts Simulation. Selection of the **Storage Rights** Extension under **MODSIM > Extensions** results in creation of a new *Storage Right Reservoir* icon in the *Node Palette Window*. It is recommended that the **Water Rights Extension** be activated along with the **Storage Rights Extension**. The new object created with the **Storage Rights Extension** is actually a representation of several objects which the user normally does not need to view (Fig. 42). However, the *Storage Right Reservoir* object can be disassembled or *broken apart* to explore the mechanisms employed in MODSIM for storage right accounting and ownerships. Users rarely need to invoke *Break Apart* when developing storage right accounts and ownerships, but it useful to show it here for illustrative purposes. Before the *Storage Right Reservoir* object is *broken apart*, the user must click **File > Save** since once invoked, the *break apart* operation cannot be undone. After *break apart* is selected, the network can be saved in a new file. After the file is saved, *right-button mouse click* displays the context menu that now includes a new item: the **Break Apart Construct**. Clicking this item displays the multi-object construct behind the *Storage Right Reservoir* icon (Fig. 43).

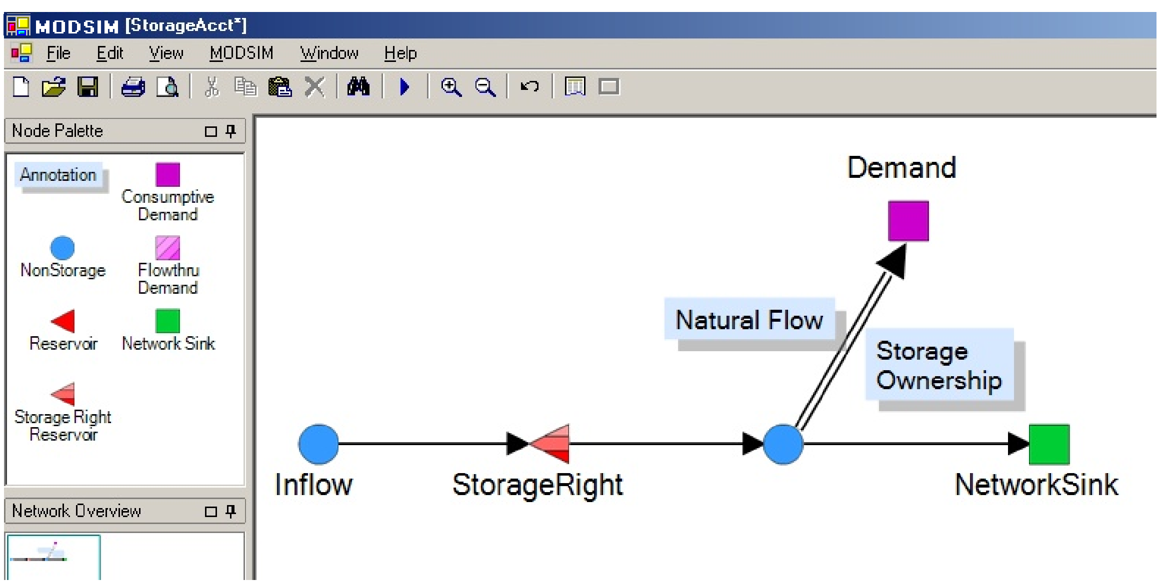


Fig. 42. Storage Right reservoir with Storage Ownership link.

Although the *Storage Right Reservoir* construct appears to change reservoir *StorageRight* to an off-stream reservoir, it in fact accurately simulates an on-stream reservoir. The *Storage Right Reservoir* construct includes *Accrual* links which are storage rights with specified decree dates and seasonal fill volumes associated with that right. Each *Accrual* link must be associated with at least one *Storage Ownership* link, and *vice versa*. The *Bypass* link represent flows that essentially *pass-through* the on-stream reservoir for release to downstream senior

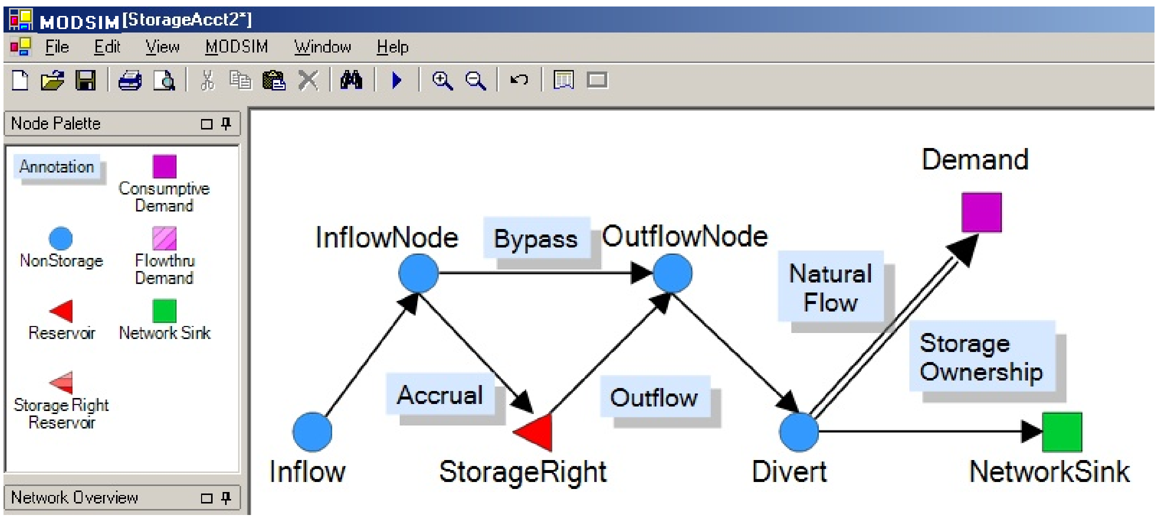


Fig. 43. Break-apart display of Storage Right reservoir.

water rights or for flood control purposes. The *Outflow* link carries releases for a particular ownership since once the in-priority storage rights have accrued to the account, water released from the account is no longer governed by water rights but rather by ownership of that account. *Storage Ownership* links are designed to convey only those releases from the storage account specifically owned by that Demand.

Storage Right Accounts. Under the **General** tab of the **Reservoir Node Properties** form for storage right reservoir, the associated *Bypass* and *Outflow* links are automatically specified, as seen in Fig. 43. The *Maximum Volume* less the *Initial Volume*, representing the carryover storage from the previous year, represents the available flow that can be accrued to the storage accounts in this reservoir during the current accrual season, which is usually the water year starting Oct. 1. The **Storage Right List** is specified under the **Storage Rights** tab of the form, with each of possibly several accrual links representing a specific storage right in the list. The *Storage Volume* associated with that right is the decreed storage right amount which is the value assigned as the *Seasonal Capacity* of the accrual link representing that storage right. If there are several storage rights, each represented by an accrual link, the total *Storage Volume* associated with those rights should not exceed the *Maximum Volume* less the *Minimum Volume* of the reservoir, representing the available active storage for the storage right accounts.

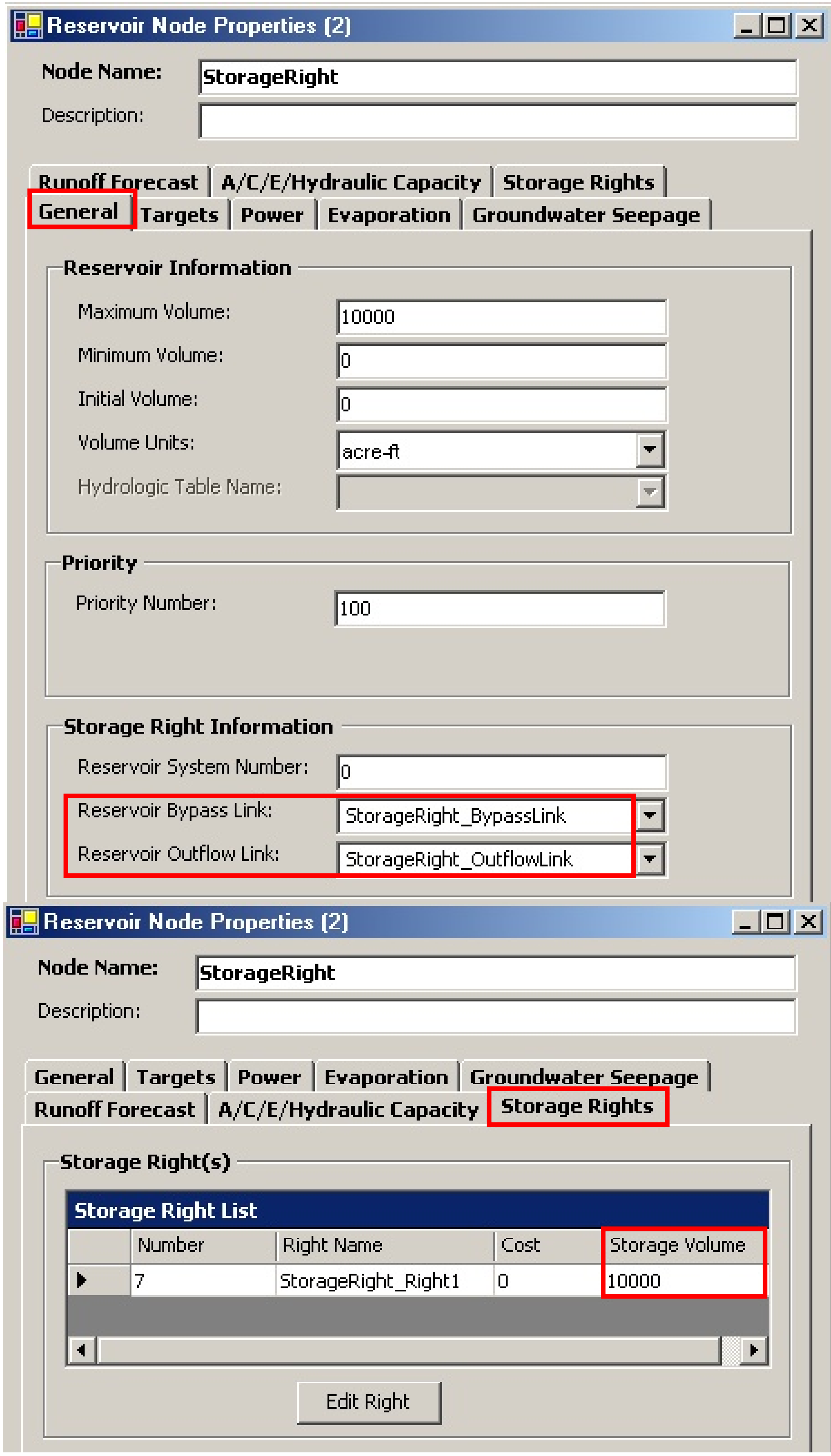
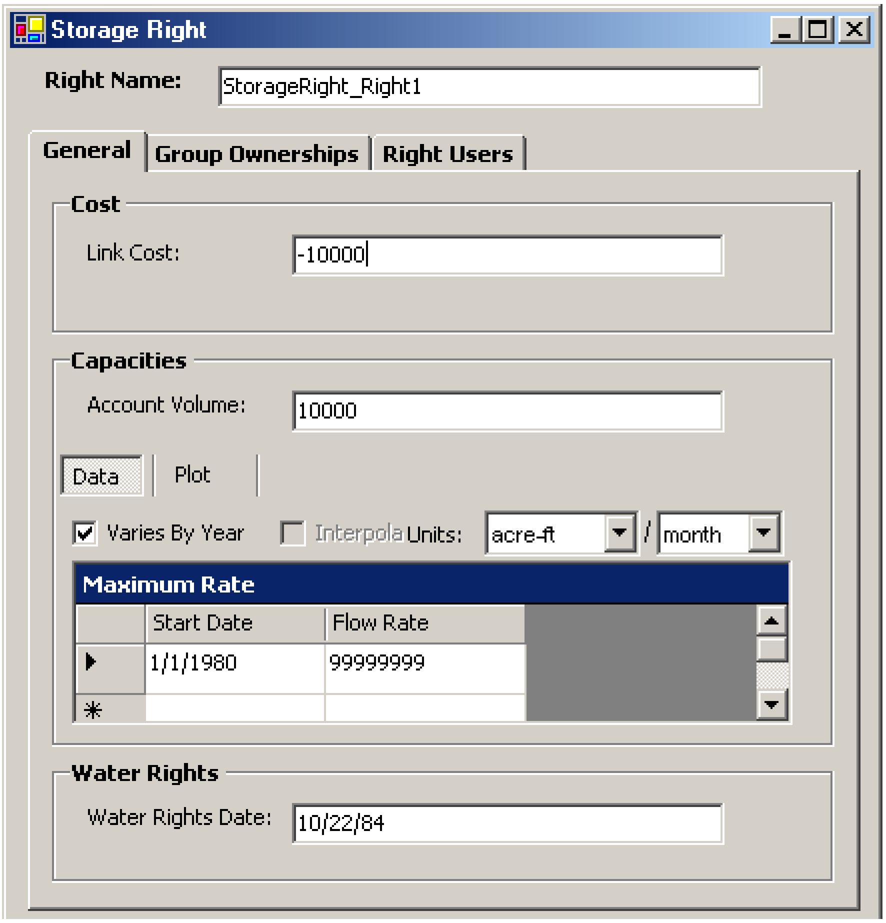
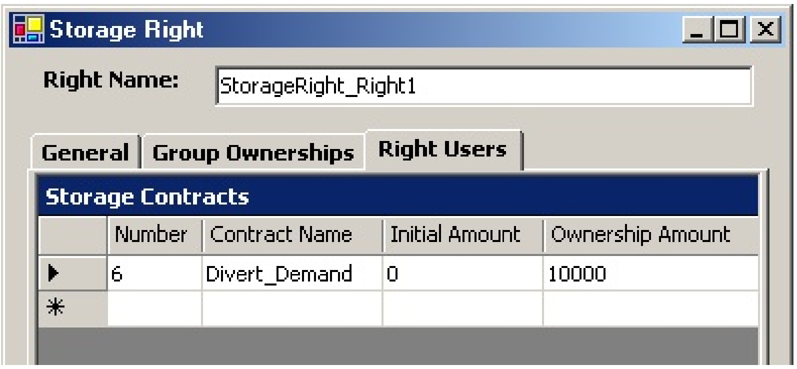


Fig. 43. Storage Right Information under the Reservoir Node Properties form.

Clicking **Edit Right** for any selected *Storage Right* in the List displays essentially the same form as the **Link Properties** form for the *Accrual* link associated with the storage right. This means that the *Accrual* **Link Properties** form can be accessed without having to utilize the *Break Apart* construct. The link cost is generated using the **Water Right Control** tool based on the decree date for that right. Again, the *Account Volume* is the same as *Seasonal Capacity* of the *Accrual* link *StorageRight_Right1*, with the name of the link corresponding to the name of the storage right. In addition to a seasonal capacity, the storage right can be further constrained by maximum flow rate for any period.



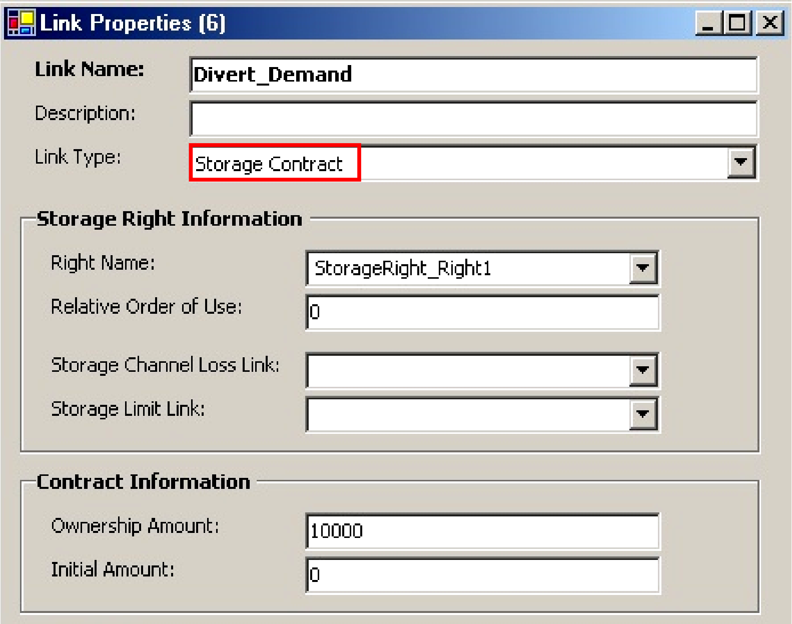
Clicking on the **Right Users** tab displays a list of the *Storage Contracts* corresponding to each storage right link accruing to the reservoir. Notice that **Group Ownerships** may be



associated with any storage right where several ownerships share in the storage right account.

Storage Ownership Links. The **Contract Name** *Divert_Demand* in this example is the *Storage Ownership* link supplying releases from the storage account to the demand. Displaying the **Link Properties** form for the *Storage Ownership* link provides **Storage Right Information** specifying the name of the storage right (i.e., the name of the accrual link to the reservoir), the *Ownership Amount*, and any carryover *Initial Amount.* For a particular demand owning several storage right accounts in the same reservoir, or possibly other reservoirs, each storage right has at least one corresponding storage ownership link conveying releases from that storage right in the reservoir to the storage right owner. Since a particular demand may own several storage accounts as well as several direct or natural flow rights, the *Relative Order of Use* entry is used to determine the order of the storage ownership links selected when storage water is needed to satisfy the demand. The storage ownership link with the lowest numeric rank number (nonnegative integer value) is used first.

A *Storage Channel Loss Link* can be specified representing a river or canal reach through which reservoir releases to the storage ownership must be conveyed that loses water due to channel seepage. MODSIM increases the reservoir release to overcome these losses, assuming sufficient storage is remaining in the account, but charges these losses to the water storage account of the storage ownership.



Designation of a *Storage Limit Link* constrains this storage ownership (and any other storage ownership links specifying the same *Storage Limit Link*) to the residual capacity of the *Storage Limit Link.* All links specifying the same *Storage Limit Link* share the residual capacity after natural or direct flow deliveries are subtracted from the capacity of the *Storage Limit Link.* This option is useful, for example, where a transbasin diversion tunnel is conveying flow to another basin, but users in the receiving basin own both natural or direct flow rights as well as storage rights in reservoirs located in the basin where flow originates. The storage ownerships in the receiving basin in this case would have to be constrained proportionately to receive only the residual capacity in the tunnel after conveyance of the natural flow rights.

Two Step Solution Process. In MODSIM, a fundamental assumption in the delivery of releases from contracted water storage accounts is that these flows are intended for *supplementary* use only. That is, in states governed by some form of the Prior Appropriation Doctrine, all direct or natural flow rights must be fully appropriated before storage accounts are used in order to avoid the prospect of abandonment proceedings. As discussed previously, at each simulation time step, solution of Eqs. 1-3 is accomplished through a series of iterations where successive approximation calculations are simultaneously performed on flow-through demands, channel losses, channel routing, and stream-aquifer interactions. With inclusion of storage right accounts providing supplemental water supplies, a two-step solution process is carried out within each successive approximations iteration: the *Natural Flow Step* and the *Storage Step*. Each of these two steps is included in the iteration counter such that the *Natural Flow Step* occurs on even numbered iterations and the *Storage Step* on odd numbered iterations, where the starting iteration number is assigned as 0 by default.

1. Natural Flow Step. The *Natural Flow Step* distributes flows based on water right priority, including accruals to the storage accounts. For the latter, the accrual links are constrained to a seasonal capacity corresponding to the size of the storage account and the available active space in the reservoir, unless the *Relax Accrual* option is invoked, in which case water can accrue as a *bookkeeping* entry to the storage right without being limited by the available active physical space in the reservoir. The rationale for invoking *Relax Accrual* is that space limitations may only be temporary due, for example, to reductions in target storage levels at the beginning of the flood season. Towards the end of the flood season when reservoirs are allowed to refill, sufficient physical space will likely be available such that at that month, the bookkeeping accrual can be adjusted to match with the physical storage in that account. Also, it is unlikely that withdrawals from storage right accounts will be needed by water users during the flood season.

As illustrated in Fig. 44, releases from storage right reservoirs are not allowed during the *Natural Flow Step* unless current storage levels exceed the target storage level, indicating that temporary storage in the flood pool must be evacuated. In this case, outflow links are only opened to accommodate flood releases. Storage ownership links conveying

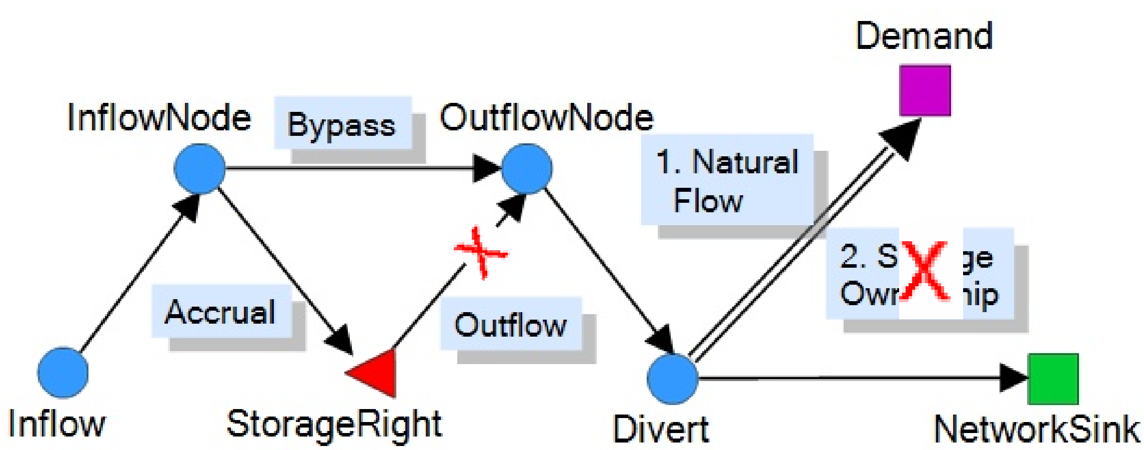
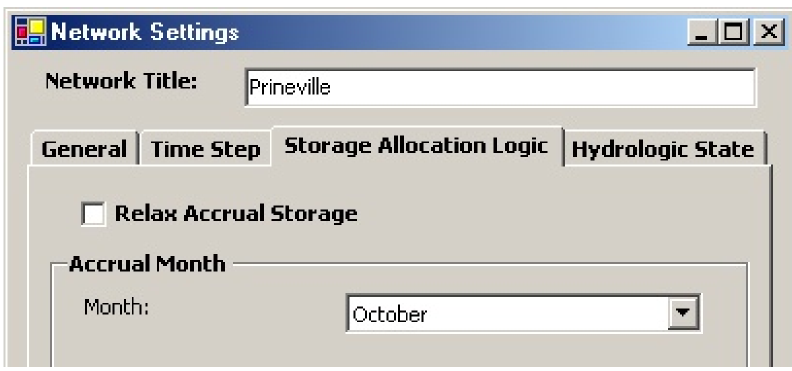


Fig. 44. Illustration of the *Natural Flow Step* in networks with storage account reservoirs.

storage account releases to downstream storage account owners are also temporarily closed during the *Natural Flow Step*. During this Step, all natural flow links to demands and accrual links to storage right reservoirs are opened with assigned costs reflecting their water right priorities. The storage right priority on accrual links competes for natural flow along with other demands with natural flow rights in the river basin. Since upper bounds on these links restrict flows to the decreed water right and/or seasonal capacity, the *Natural Flow Step* insures that all legal entitlements based on direct or natural flow water rights are correctly maintained. For this reason, the *Natural Flow Step* can be referred to as a *bookkeeping* or *paper accounting* step.

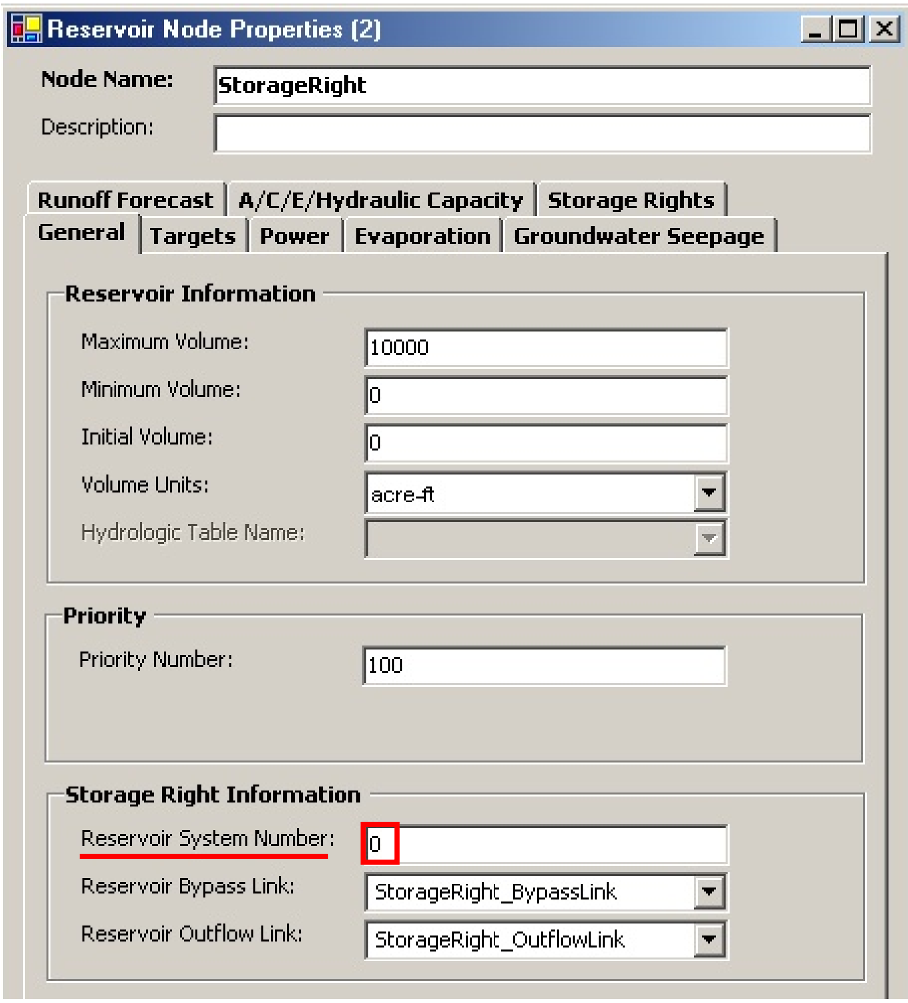
The **Accrual Month** as the beginning time step of the accrual season is selected by the user under the **Storage Allocation Logic** tab located on the **Network Settings** form. Clicking the *checkbox* next to **Relax Accrual Storage** allows accrual to the storage account up to the seasonal capacity without regard to whether the water can be physically stored in that time step, whereas leaving it unchecked restricts accruals to the available active capacity. Finally, accrual can be constrained by outstanding last-fill water which is explained subsequently under the *Rent Pool* topic.



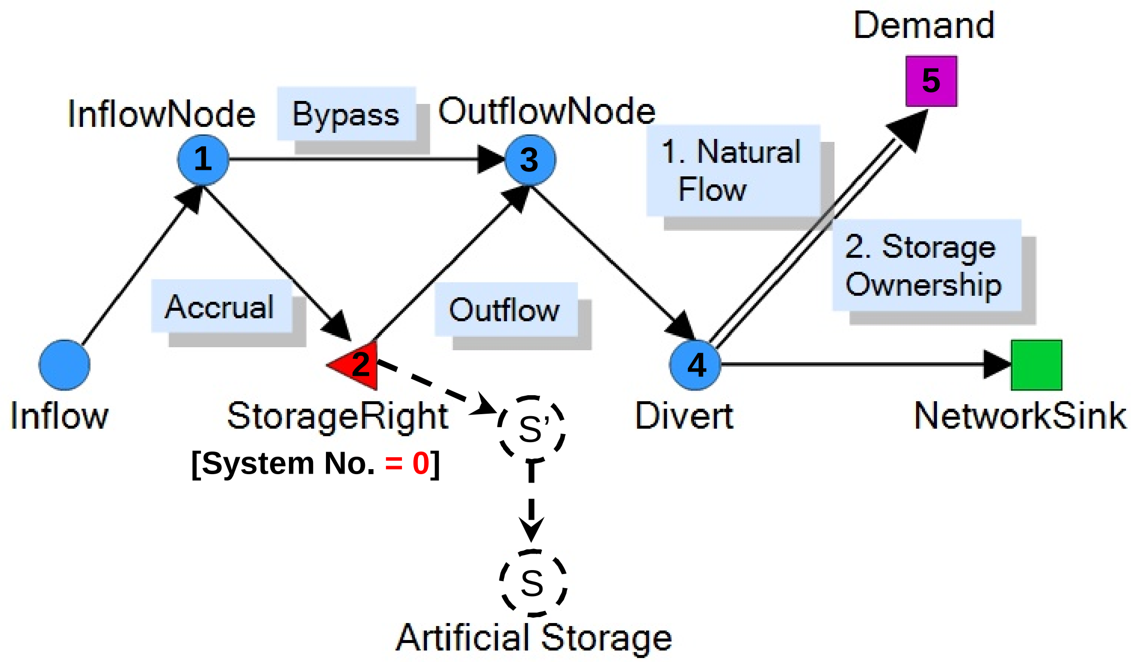
During the *Natural Flow Step*, artificial target storage links are opened with an upper bound based on either explicit storage targets set in the **Reservoir Node Properties** form, or conditional target storage levels based on *Hydrologic State* indices. The cost assigned to the artificial target storage link (i.e., link [**S'**,**S**] in Fig. 4) is set to a relatively neutral value of -49000 by default (corresponding to a reservoir priority $OPRR_i$ = 100) so it can compete equally with artificial demand links which are also set to -49000 by default. It is assumed, particularly when demands have multiple water rights, that water allocation priorities are based on link costs directly assigned to the natural flow and storage right accrual links based on water right decree date using the **Water Rights Editor**, and not on priorities assigned to the demand and reservoir nodes.

After completion of the *Natural Flow Step*, the flow in each *Accrual* link is credited proportionately (according to the amount of ownership) to the accounts associated with those *Storage Ownership* links that specify ownership of that particular storage right. The total ownership amounts drawing on that storage right should of course equal the volume of that storage right.

2. Storage Step. The distribution of natural flow or direct flow rights from the *Natural Flow Step* is used to set lower bound constraints on natural flow right links in the *Storage Step*. This assures that water right entitlements are legally satisfied while introducing storage water and physical operational objectives for the reservoir system. For the *Storage Step*, the setting of bounds on accrual links to and outflow links from storage right reservoirs depends on specification of a *Reservoir System Number* for that reservoir, which is entered under the **General** tab of the storage right **Reservoir Node Properties** form.



Zero System Number. As shown in Fig. 45, storage right reservoirs assigned a **zero** system number have the upper bound on the outflow link set to the maximum of: (i) any flood control evacuation volume; (ii) the sum of the upper bounds on the storage ownership links, which are calculated as the smaller of the remaining unsatisfied demand (after the *Natural Flow Step*) and the current balances in the associated reservoir storage accounts. Lower bounds on inflow accrual links to storage right accounts are set to accruals calculated during the *Natural Flow Step*. Upper bounds on the natural flow links remain at the user-specified maximum or variable capacity. In effect, reservoirs assigned **zero** *Reservoir System Numbers* are constrained to an explicit bookkeeping method



Link $[i,j]$	**Lower Bound** l_{ij}	**Upper Bound** u_{ij}	**Unit Cost** c_{ij}
Accrual $[1,2]$	q_{12} [from *Natural Flow* Step]	Seasonal Capacity Balance	Based on Water Right Priority = – 50000 to – 30000
Artificial Storage $[2,\mathbf{S}]$	$S_{j,\min}$	User Assigned Target Storage or based on Hydrologic State T_j	User Assigned Storage Priority = –50000 to –30000
Outflow $[2,3]$	0	max [• Storage ownership link bounds (total) • Flood control evacuation]	0
Natural Flow $[4,5]^1$	$q_{4,5}$ [from Natural Flow Step]	Decreed Water Right Entitlement $q^1_{4,5\,\max}$	Based on Water Right Priority = – 50000 to – 30000
Storage Ownership $[4,5]^2$	0	min [• Storage ownership amount Shortage after *Natural Flow* step • Reservoir account balance]	≅ –200000

Fig. 45. Illustration of the *Storage Step* in networks with storage account reservoirs assigned **zero** *System Numbers*.

whereby the *paper* accounting exactly corresponds to the *physical* accounting in the storage right reservoir.

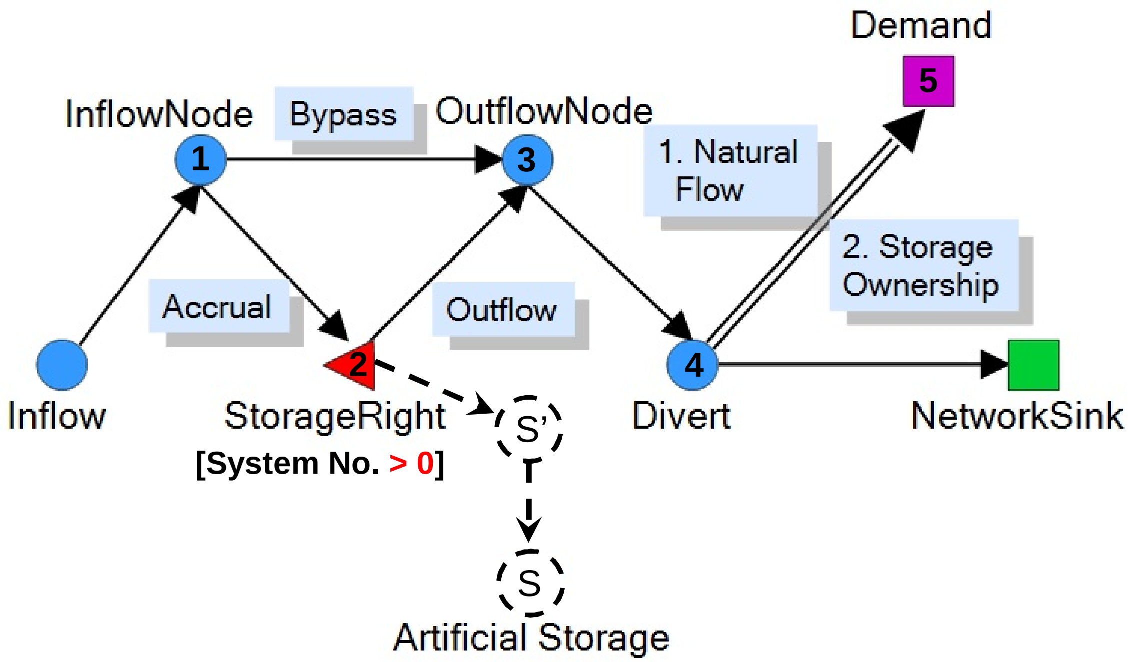
For reservoirs with **zero** *Reservoir System Numbers*, each demand with storage ownership links terminating at that node is checked to determine if shortages remain after completion of the *Natural Flow Step*. In this case, the demand is entitled to receive releases from storage rights assigned to their storage ownership links. One by one, the storage ownership links to the demand are opened with an upper bound set to the *smaller* of: (i) the storage account balance for that storage right; (ii) the remaining demand after satisfaction of any natural or direct flow rights during the *Natural Flow Step*. The order of storage ownership link selection is based on the ranking defined by the *Relative Order of Use* entry in the **Link Properties** form of each storage ownership link, with lower integer values indicating a higher ranking. Prior to the network solution, a large negative cost of approximately -200,000 is assigned to the storage ownership links to insure that only these links receive releases from the storage right accounts, rather than providing additional flows to the natural flow links. The formula for assigning the storage ownership link costs is:

$$c_{ij} = -200000 - \textit{link no.} + \textit{link cost}$$

where *link no.* is an arbitrary number assigned to the link by MODSIM and *link cost* is the value entered in the *Relative Order of Use* box in the **Link Properties** form. The primary purpose of this equation is to assign unique costs to the storage ownership links so as to obtain unique solutions from the network flow solver. Unique flow allocations to the storage ownership links are only necessary when the reservoir system is being drained and insufficient storage is available to satisfy all the storage ownership accounts. The large negative cost assigned to the storage ownership links guarantees that these links are filled before any additional releases are used by the natural flow links.

<u>Nonzero System Number</u>. Setting a group of reservoirs with the same **nonzero** *Reservoir System Number* provides for implicit exchanges between the reservoirs in that group or *system*. This means that water accrued to a storage right in a particular reservoir during the *Natural Flow Step* may actually be physically stored in another reservoir during the *Storage Step*. For example, even though a downstream reservoir may have a senior storage right, it may be advantageous for efficient reservoir operations to physically store water in an upstream reservoir and account for the storage accrual as if it occurred in the downstream reservoir. Flood control requirements, instream flow demands from contracted water, and other operational considerations can require water belonging to a contract holder in one reservoir to be physically stored in another.

Fig 46 shows that for the **nonzero** *Reservoir System Number* case, artificial target storage links are opened and set with an upper bound based on either explicit storage targets set in the **Reservoir Node Properties** form, or conditional target storage levels based on *Hydrologic State* indices. The cost assigned to the artificial of the target storage link (i.e., link [**S’**,**S**] in Fig. 4) is also based on the formula of Eq. 4, except that the constant 50000 in the formula is replaced with 70000. This modified formula has the effect of allowing storage ownership links to be satisfied to the physical capability of the



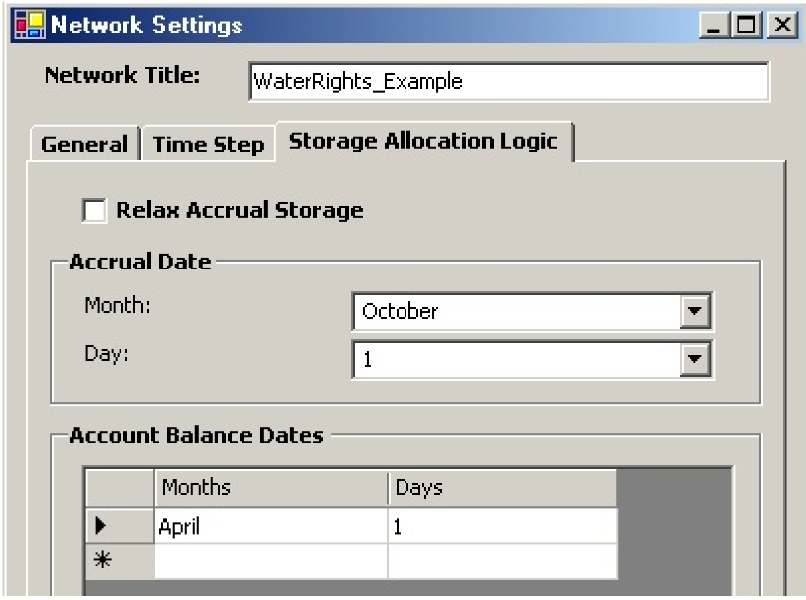
Link $[i, j]$	**Lower Bound** l_{ij}	**Upper Bound** u_{ij}	**Unit Cost** c_{ij}
Accrual $[1,2]$	0	Seasonal Capacity Balance	Based on Water Right Priority $= -50000$ to -30000
Artificial Storage $[2, \mathbf{S}]$	$S_{j,\min}$	User Assigned Target Storage or based on Hydrologic State T_j	User Assigned Storage Priority $= -70000$ to -50000
Outflow $[2,3]$	0	*M* [large number]	0
Natural Flow $[4,5]^1$	$q_{4,5}$ [from Natural Flow Step]	Decreed Water Right Entitlement $q^1_{4,5\max}$	Based on Water Right Priority $= -50000$ to -30000
Storage Ownership $[4,5]^2$	0	min [• Storage ownership amount Shortage after *Natural Flow* step • Reservoir account balance	$\cong -200000$

Fig. 46. Illustration of the *Storage Step* in networks with storage account reservoirs assigned **nonzero** *System Numbers*.

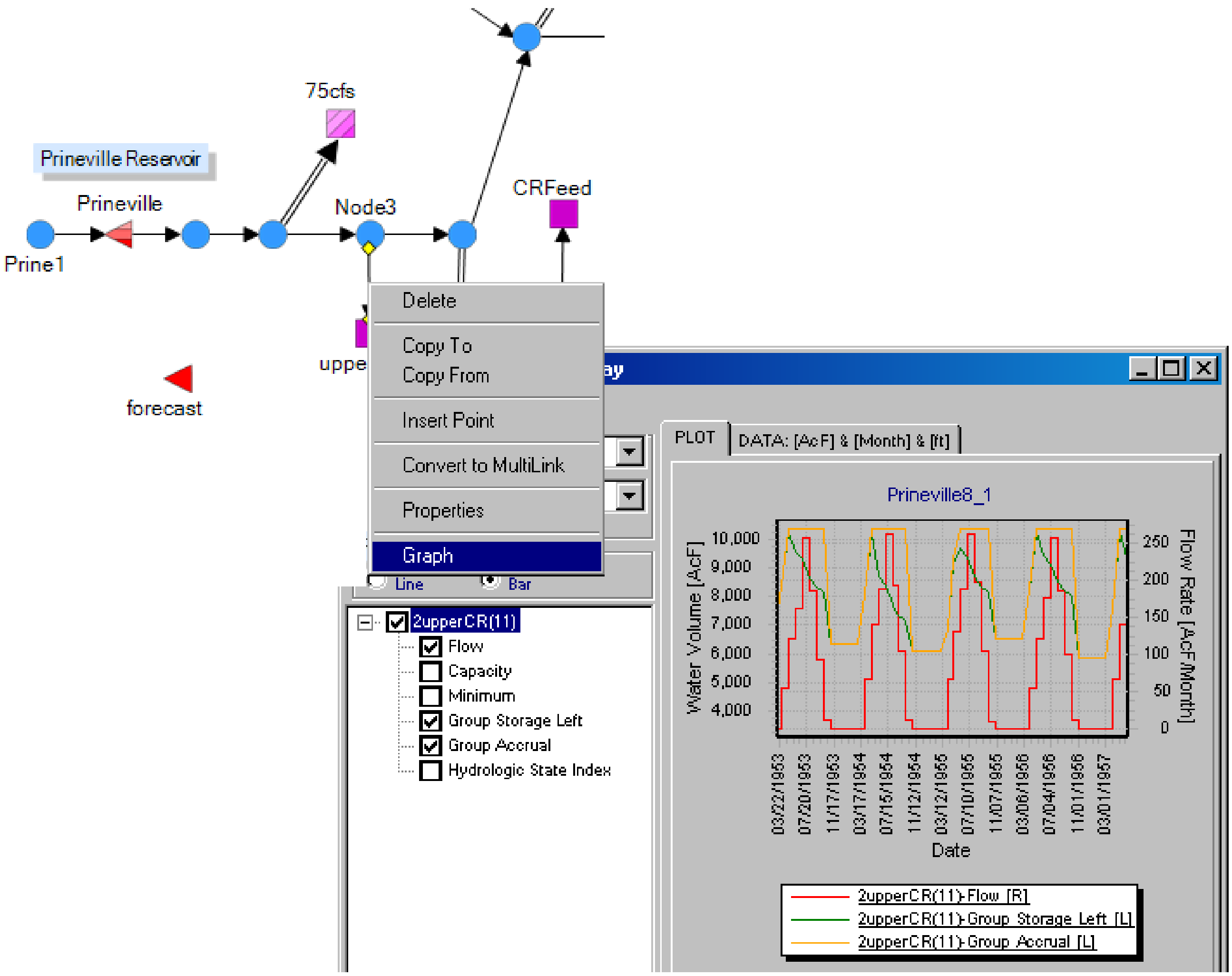
system (since their costs are on the order of -200000), while not allowing natural flow rights to be satisfied by reservoir releases. The relative cost of the target storage link in relation to other reservoirs in the system with the same **nonzero** *Reservoir System Numbers* determines if a given reservoir is drafted to meet storage water demands, irrespective of the storage right accrual in that reservoir. In this case, upper bounds on outflow links are assigned a large value and not restricted by the total ownerships in that storage right reservoir, as is the case for reservoirs with **zero** *Reservoir System Numbers*. Also, accrual link upper bounds are set with upper bounds equal to the seasonal capacity or storage right, but lower bounds are set to zero rather than explicitly defined by the accrual occurring during the *Natural Flow Step* as in the **zero** *Reservoir System Number* case. Also, releases from a storage right reservoir are no longer restricted to just those storage contracts with ownerships in that reservoir. This allows *exchanges* between reservoirs whereby *physical* storage water can be released from a storage right reservoir for delivery to a storage ownership link even though the corresponding *paper* storage right account may exist in another reservoir with a **nonzero** *Reservoir System Number*. In spite of the fact that the actual release occurred from another reservoir, the storage right account is appropriately debited by the MODSIM storage accounting logic.

Convergence of iterative calculations on flow-through demands, return flows, depletions from groundwater pumping, channel losses, and channel routing is checked after the *Storage Step*, rather than after the *Natural Flow Step*. If the percent absolute difference of flow values from two successive *Storage Step* iterations is less than a specified tolerance, the time step solution is complete. If not, appropriate information is stored in memory, link costs and bounds are reset for another *Natural Flow Step* iteration, and the sequence is repeated until the convergence criteria are satisfied.

<u>Account Balance Month</u>. After a reservoir has been allowed to refill from flood control drafts, the total amount of *physical* water available in the reservoir needs to match the *paper* accrual for the season. Account balancing and **nonzero** *Reservoir System Numbers* allow the user to simulate these kinds of river basin administrative procedures. Clicking the **Storage Allocation Logic** tab under **MODSIM > Network Settings** allows entry of *Account Balance Months* which specify when MODSIM performs bookkeeping calculations to balance the *physical* and *paper* or *theoretical* accounts in each storage right reservoir. The default setting where no account balance months are specified results in the *Account Balance* routine in MODSIM being run at the end of each simulation time step. For monthly time steps, any number of months can be selected by the user. Daily or weekly simulation time steps require specification of account balance *days* along with the calendar month specification. In the time step when account balancing is required, a number of reservoirs can be pooled in a system of reservoirs with the same **nonzero** *Reservoir System Number*. When the *Account Balance* logic is called, all storage accounts for all reservoirs with the same **nonzero** *Reservoir System Number* are summed, and all physical end-of-period contents in these reservoirs are also totaled. A ratio is then computed and all storage accounts appropriately adjusted to equalize the physical and paper accounting.



Storage Account Output Results. After executing a MODSIM network with storage rights accounting, output information on the storage accounts is not found in the output files for the storage right reservoir. Rather, this output information is found by viewing the output tables and graphs associated with the storage ownership links, as seen below.



D. Exchanges

Implicit Exchanges. As discussed previously, the use of nonzero system numbers in MODSIM allows *implicit* exchanges to occur whereby natural flow rights are satisfied in priority and storage ownerships receive the reservoir releases they are entitled to by contract. However, flows received by the storage ownerships may not be releases from the reservoirs within which they own storage rights. Exact correspondence between physical accounting and *paper* accounting can be relaxed over several time periods, with Account Balance Dates specified under **MODSIM > Network Settings > Storage Allocation Logic**. In this way, water may be implicitly exchanged between storage ownerships in reservoirs with the same nonzero system number. This flexible approach to exchanging water allows MODSIM to determine mechanisms that minimize shortages to junior water right holders and protect storage account owners, while providing reservoir operators the ability to regulate their systems for other objectives such as flood control and hydropower generation. These water right and storage contract accounting procedures determine water exchanges that maximize delivery efficiency and assure that each user receives their entitled portion of the water supply. In effect, the *paper* accounting or bookkeeping adjustments for entitlements in the context of implicit exchanges is completed after the physical operation has taken place.

Explicit Exchanges. In some river basins, exchanges must be *explicitly* defined and accounted for in order to be legally acceptable. In this case, the *paper* accounting for water distribution in each instance must be defined and constrained according to the physical exchange capacity. Assigning **zero** *Reservoir System Numbers* for reservoirs accomplishes explicit exchange mechanisms. For example, as illustrated in Fig. 47, diversion to a storage contract owner with junior natural flow rights may actually exist upstream of the storage right reservoir right in which the ownership is held. Although the storage right owner is unable to directly receive releases from the storage right account, an explicit exchange can occur whereby a downstream senior water right holder receives releases from the storage account *in lieu* of out-of-priority diversions to the upstream storage account owner. This will occur since the storage ownership link connected to **Junior** demand is assigned a large negative cost. Since all natural flow links are assigned lower bounds equaling the legally entitled flow calculated during the *Natural Flow* step, this exchange will not interfere with senior water right holders. The exchange will only occur to the extent that there are sufficient flows upstream of the reservoir that can be diverted by **Junior** *in lieu* of reservoir releases that can satisfy the **Senior** water right.

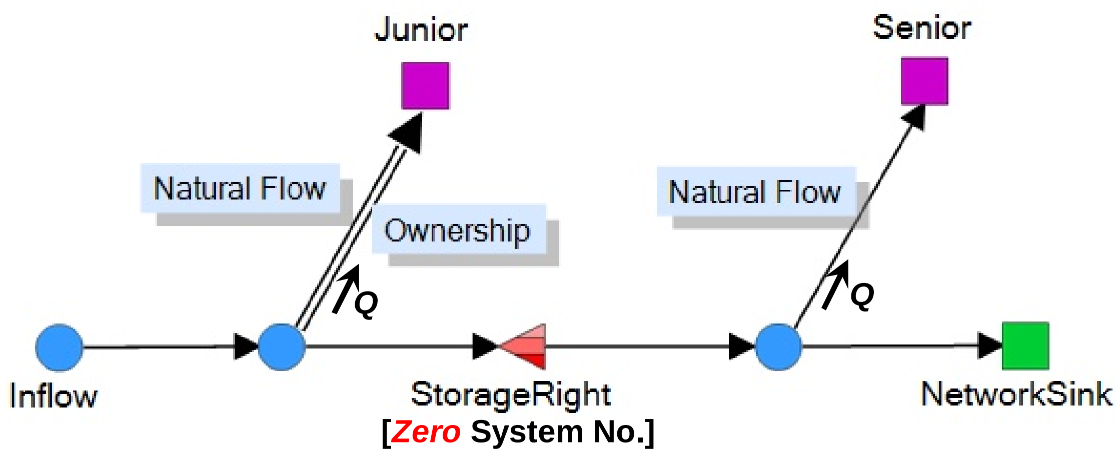
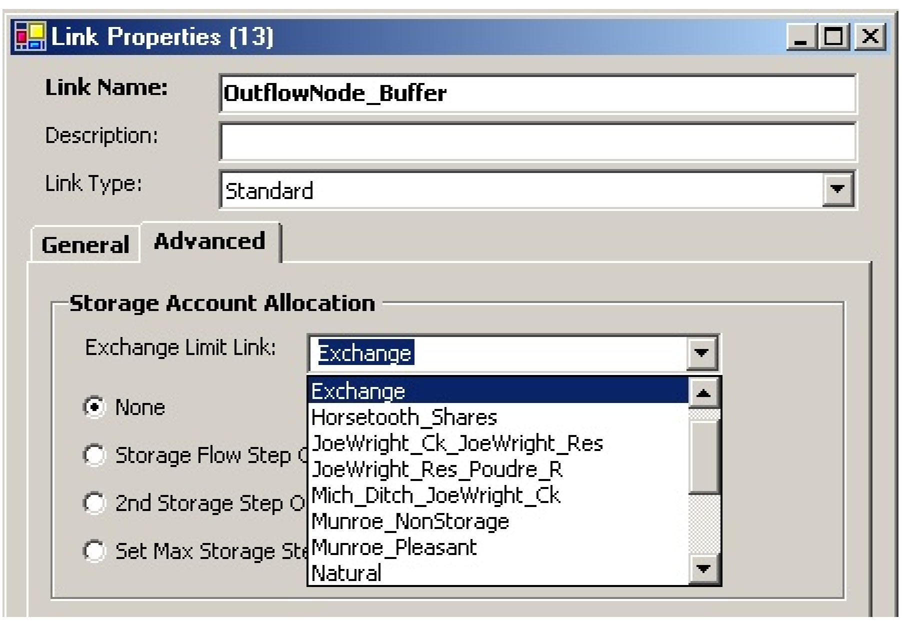


Fig. 47. Illustration of explicit exchanges for storage account reservoirs with **zero** *Reservoir System Numbers*.

Exchange Limit Link. MODSIM provides several mechanisms for simulating explicit exchanges. Clicking the **Advanced** tab on a **Link Properties** form allows specification of an *Exchange Limit Link*. This activates a *Watch Logic* procedure in MODSIM whereby current flow in the specified *Exchange Limit Link* in the previous iteration is assigned as the upper bound to the link that is *watching* the flow in that link. This tool simulates explicitly defined exchanges whereby the allowed flow at a certain location in the network is contingent on flows elsewhere in the network. This logic can be incorporated into small disconnected networks with flow-through demands to simulate constructs such as accumulated flow credit accounts, shared water rights between demands, and other complex exchange mechanisms. It provides a flexible means of tying physical operations or water supply accounting at a node to conditions and operations in other portions of the network.



By default, return flows (determined from previous iterations) become part of the natural flow to be distributed in the *Natural Flow Step*, which includes return flows from storage account diversions. Several options exist as to when the exchange limit mechanism is imposed:

- **Storage Flow Only** - This box is checked if flow in this link is only permitted during the *Storage Step*. For example, if this switch is set and the link terminates at a flow-through demand, then flow in this link is returned to the river at designated return nodes during the next *Storage Step*, rather than the immediately following *Natural Flow Step*. This may be useful if it is desired that a strict accounting is maintained for instream flow requirements satisfied from storage right accounts, thereby preventing these flows to be taken during the *Natural Flow Step* according to water right priority.
- **2nd Storage Step Only** – It is possible for a *2nd Storage Step* to occur for exchanges with flow-through demands that have storage ownerships. This allows water to be brought to the flow-through demand only after there is insufficient flow after the *1st Storage Flow Step* to satisfy the demand. Since flow-through demands are nonconsumptive demands, it is desired to determine if downstream demands, including those with storage ownerships, can *pull* sufficient water through the instream flow reach that will also result in satisfaction of the flow-through demand.
- **Set Maximum Storage Step = Natural Flow** - Check this box if the flow in this link is to be determined during the Natural Flow Step and then held to that specific amount during the storage step. In this case, the upper bound on the link is set to the amount that flowed through the link in the *Natural Flow Step* iteration.

Exchange Credit Node. Another form of *Watch Logic* in MODSIM can be invoked by selection of *Exchange Credit* as the *Demand Definition Type* in the **General** tab of the **Demand Node Properties** form, which then allows users to specify an *Exchange Credit Node* located elsewhere in the network. As an example, Fig. 48 shows an offstream reservoir owned by *NPoudre_Irrig*, but from which *NPoudre_Irrig* is unable to directly receive releases to meet their demands. An exchange agreement can be entered into between *Ft_Collins* and *NPoudre_Irrig* whereby releases can be made from the reservoir for delivery to *Ft_Collins* in lieu of direct diversions to *NPoudre_Irrig* of flows that Ft_Collins owns as a senior right. The flow-through demand *Exchange* serves to facilitate the exchange process, where diversions to *NPoudre_Irrig* are credited to the Exchange node and then transferred to *Ft_Collins*. The portion of the demand satisfied during the previous iteration at *NPoudre_Irrig* becomes the actual demand at the *Exchange* flow-through demand node. In this case, any prespecified demands for the *Exchange* flow-through demand node are replaced by the actual demand satisfied at *NPoudre_Irrig*.

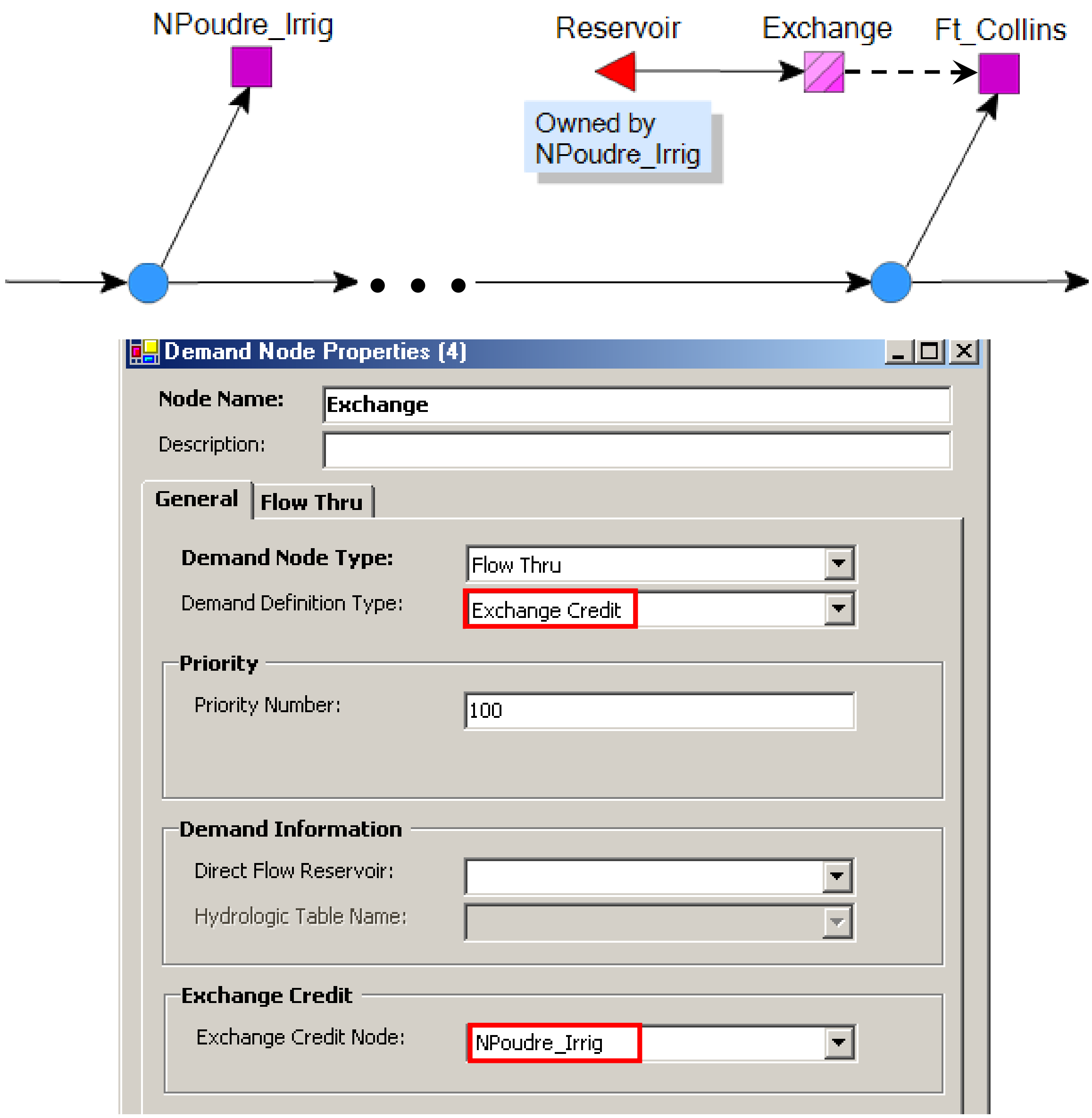


Fig. 48. Illustration of exchange between water users using the Exchange Credit feature.

Watch Logic Calculator. MODSIM provides a *Watch Logic Calculator* for defining more complex conditional relationships where flow requirements at a particular location are based on flow conditions at various links throughout the network. As shown in Fig. 49, the *Demand Definition Type* can be specified as *Watch Links* in the **Demand Node Properties** form, which creates a new **Watch Links** tab. The *Watch Logic Calculator* under the new *Watch Links* tab shown in Fig. 50 performs calculations according to the following general formula:

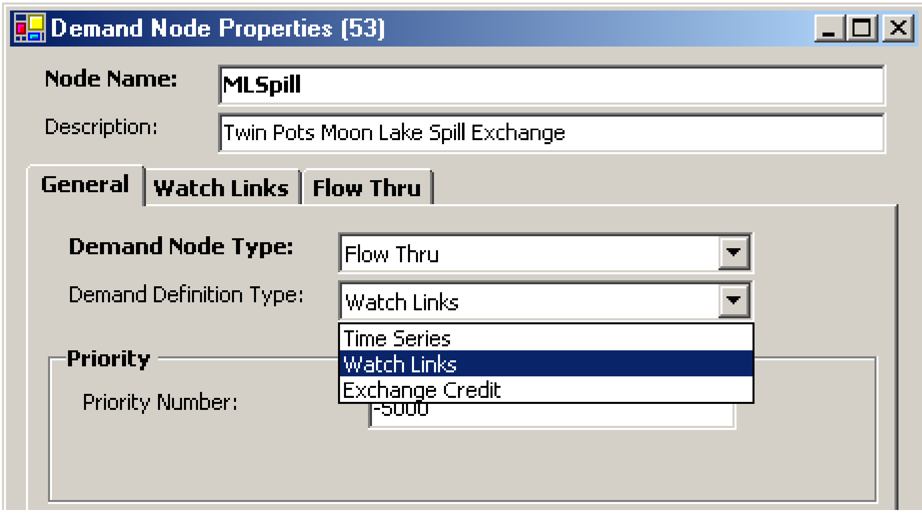


Fig. 49. Specification of *Watch Links* as a *Demand Definition Type*.

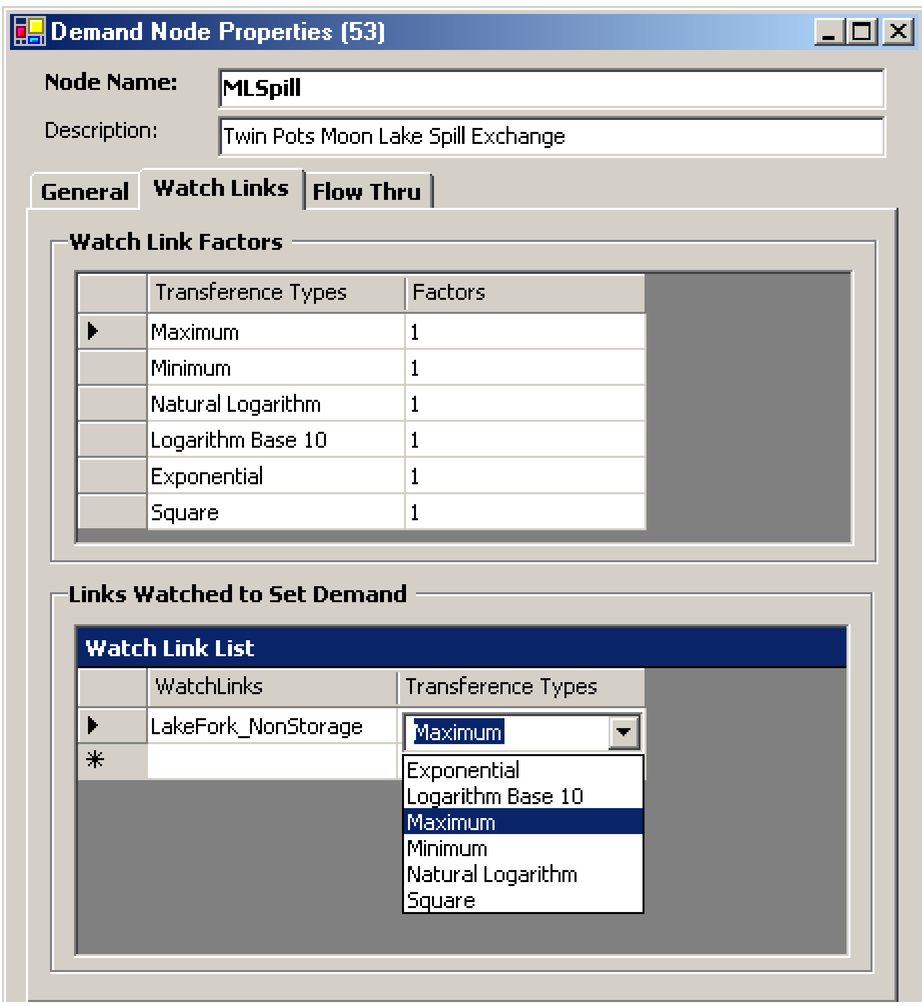


Fig. 50. Watch Logic Calculator for conditioning a demand on flows in links elsewhere in the network.

$$D = w_{max} \cdot \max\left(\forall q_l \mid l \in A_{max}\right) + w_{min} \cdot \min\left(\forall q_l \mid l \in A_{min}\right) + w_{ln} \cdot \ln\left(\sum_{l \in A_{ln}} q_l\right)$$
$$+ w_{log} \cdot \log\left(\sum_{l \in A_{log}} q_l\right) + w_{exp} \cdot \exp\left(\sum_{l \in A_{exp}} q_l\right) + w_{sqr} \cdot \left(\sum_{l \in A_{sq}} q_l\right)^2 \quad (31)$$

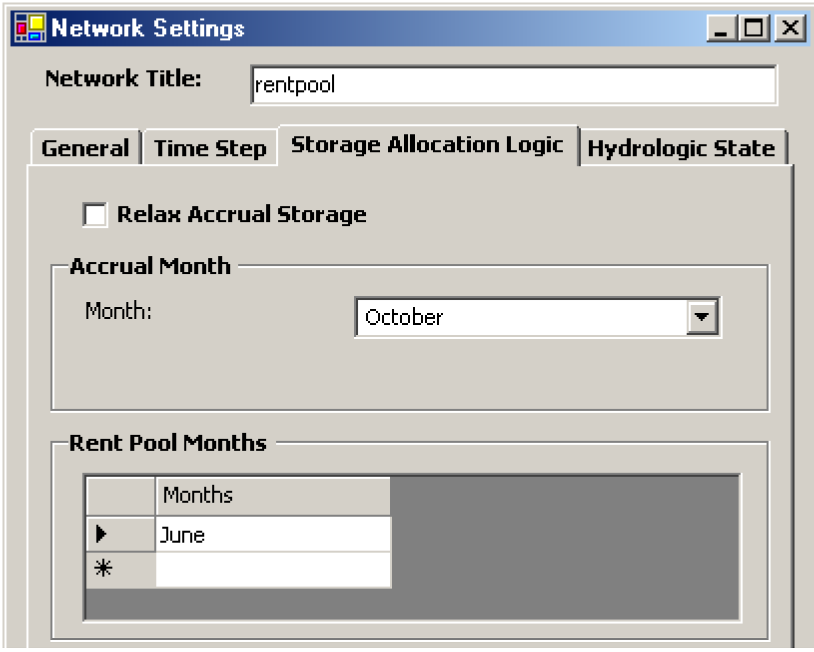
where D is the demand being calculated for the selected Demand node; w_{max}, w_{min}, w_{ln}, w_{log}, w_{exp} and w_{sq} are weighting *Factors* associated with the Maximum, Minimum, Natural Logarithm, Logarithm Base 10, Exponential, and Square *Transference Type* operators, respectively; and the sets A_{max}, A_{min}, A_{ln}, A_{log}, A_{exp}, and A_{sq} represent the arcs selected for inclusion of calculations under that *Transference Type* operator, respectively. For example, the notation $\max\left(\forall q_l \mid l \in A_{max}\right)$ refers to selection of the maximum flow occurring among any of the links included in the user defined set of links A_{max} for the current simulation time step.

To select more than one link associated with a particular *Transference Type* operator, users simply click a new row in the *Watch Link List*, select the same *Transference Type* operator under the *Transference Type* column, and then click the drop down arrow under the *WatchLinks* column to select another link anywhere in the network. In this way, users can select as many links as desired to be associated with any particular *Transference Type* operator. Although several of these operators involve floating point or real number calculations, the resulting demands are rounded to the nearest integer value if the user has selected integer accuracy under the **MODSIM > Network Settings > General** tab. Although the *Watch Logic Calculator* provides a broad range of functions and operators for developing conditional rules, more complex rules can be defined using the **Custom Code** capabilities of MODSIM. As with *Exchange Credit* nodes, any demands calculated using the *Watch Logic Calculator* take precedence over demand time series data included in the **Demand Node Properties** form.

E. Rent Pool and Water Service Contracts

Rent Pool and Water Banking. The *Rent Pool* amounts to a temporary transfer of accrued storage water from one owner to another demand. The intent is to allow users in a given water year with an abundance of water entitlements to submit an amount of storage water to the Rent Pool. Water bank or Rent Pool administrators find a buyer (i.e., a user short of water entitlements) and the transfer of entitlement is made. The price paid for Rent Pool water is controlled by the rules established by the river basin water users. Some water users have more water entitlements than they need in an above average water supply year, whereas in low runoff water years, there may be little, if any, available for rent pool activity. Some water users with insufficient entitlements in below average water years will rent water when available and retain any storage contract water they own as carryover into a low runoff water year.

Rent Pool transfers are decided on a particular date(s) of the year which is set via **Network Settings > Storage Allocation Logic**. For simulation time steps less than a month, users enter month and day associated with this date when the Hydrologic State index is used to select amounts either for subscribing or contributing to the Rent Pool.



Each storage right conceptually has its own Rent Pool. All contributions and subscriptions are summed for a storage right and a ratio is applied to the larger of these sums so they are equal. Accrual to the storage right account is debited against the contributor and credited to the renter. From this time on until the next year, the renter is entitled to use the rent water as if it was a storage ownership contract. Rental water is charged for evaporation and carriage loss similar to other storage water.

In order to subscribe to the Rent Pool, negative entries are made in the Rent Pool Limits, indicating the maximum amounts to be subscribed during various hydrologic conditions. Positive Rent Pool limits indicate a contribution to the Rent Pool. Consider the example network shown in Fig. 51, where the two demands **Owner** and **Renter** each have natural flow rights, but only **Owner** has a storage rights account. **Renter** is a water user that is

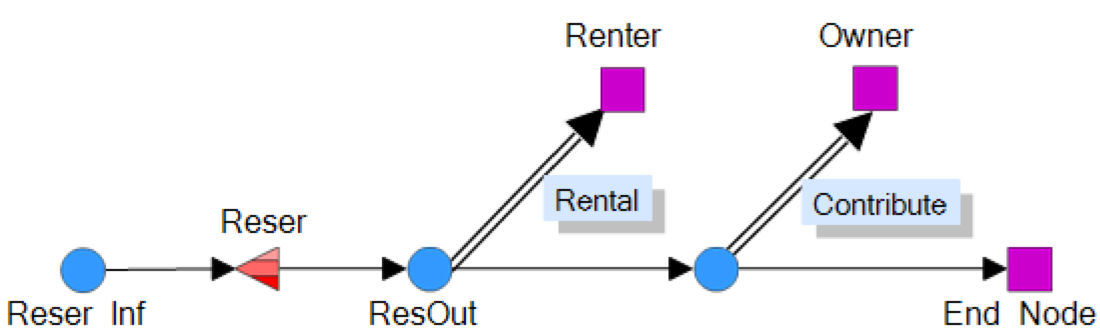


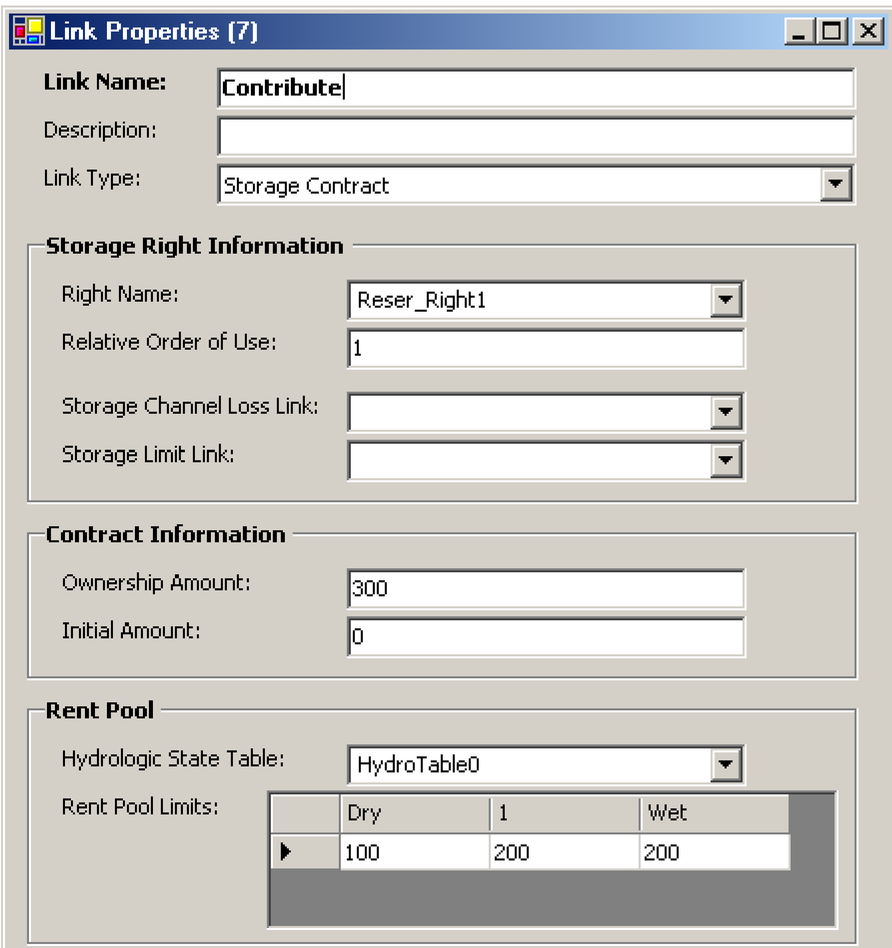
Fig. 51. Example network illustrating Rent Pool operations.

short on water entitlements and therefore desires to subscribe to the Rent Pool. **Owner** currently has two high priority Natural Flow rights and is therefore willing to contribute a portion of his storage ownership to the Rent Pool.

Links between NonStorage & Owner

		Link Name	Link Type	Cost	Order of Use	Channel Type
▶	2	NatFlow_1	Natural Flow	-10000	NA	Default
	7	Contribute	Storage Contract	NA	1	NA
	9	NatFlow_2	Natural Flow	-9997	NA	Default

Positive entries are made in the **Rent Pool Limits** for each Hydrologic State in the **Link Properties** form for the storage ownership link **Contribute**, but not to exceed the total **Ownership Amount**. The **Right Name** called *Reser_Right1* is possessed by the **Owner** demand and represents an account in the storage right reservoir **Reser**.

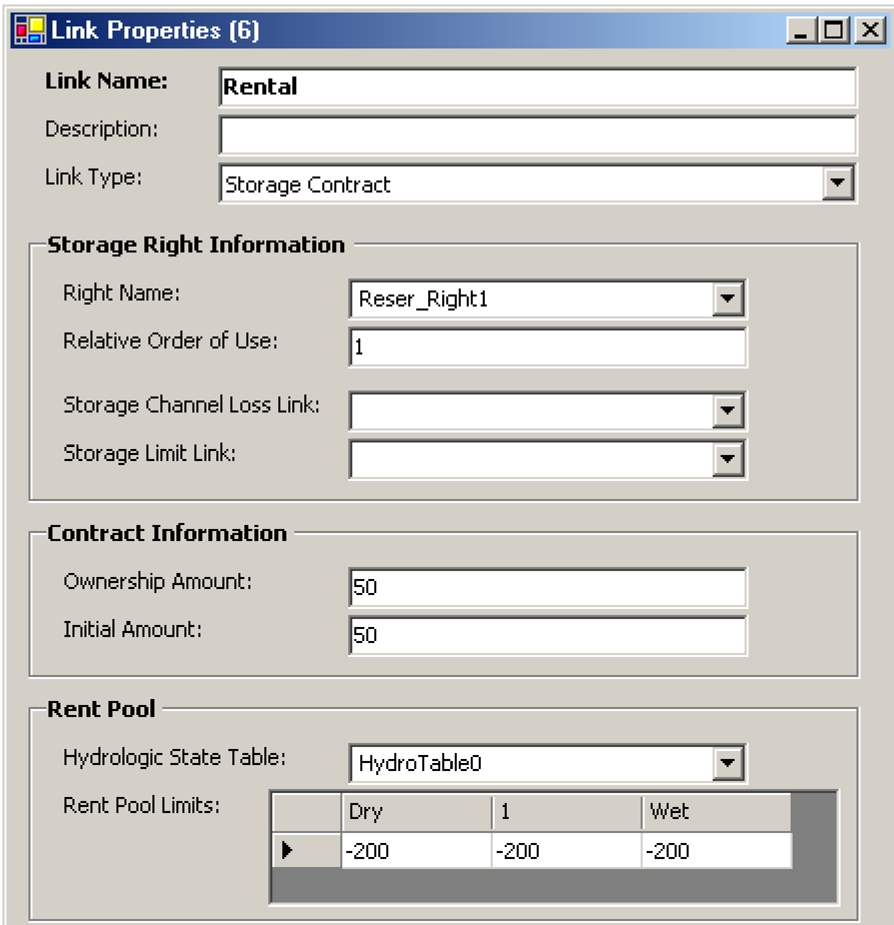


The water user **Renter** also owns two Natural Flow rights, but they are junior to those of **Owner**. A storage contract link entitled **Rental** is created, even though the demand **Renter** does not actually own any storage rights. Opening the **Link Properties** form for the link **Rental**, the **Link Type** is specified as *Storage Contract* and the **Right Name** of *Reser_Right1* is also listed, even though this account is actually held by **Owner**.

Links between ResOut & Renter

		Link Name	Link Type	Cost	Order of Use	Channel Type
▶	1	Natural_1	Natural Flow	-9999	NA	Default
	6	Rental	Storage Contract	NA	1	NA
	8	Natural_2	Natural Flow	-9996	NA	Default

However, entries under the **Rent Pool Limits** are entered as negative values, indicating that Renter is a subscriber to the Rent Pool since **Owner** is willing to contribute some accrued storage water to the Rent Pool, depending on the water supply in a given year. The *Hydrologic State* in this example is based only on reservoir contents. Again, **Renter** does not have an ownership contract entitlement and therefore wants to subscribe to storage water from the Rent Pool.



If the demand for **Renter** cannot be fully satisfied from Natural Flow entitlements, the **Rental** link is made available to satisfy the remaining demand up to the amount **Owner** is willing to contribute. Note that a particular link cannot have both negative and positive *Rental Pool Limits*; i.e., a link can specify either a subscription or contribution to the Rent Pool, but not both. As seen in this example, the Rent Pool Limit can vary with the Hydrologic State index and is reset every year on the date specified under **MODSIM** > **Network Settings** > **Storage Allocation Logic** > **Rent Pool Dates**. The Rent Pool routine can be called more than once a year. The first time the Rent Pool routine is called after the Month of Accrual, any unused Rent Pool water from the previous year transfer is returned to the contributors in proportion to the amount they contributed; after this, the present season transfers are carried out. Subsequent calls to the Rent Pool routine will incrementally transfer any additional accrual the contributors are credited with up to the Rent Pool Limit amount. Reservoir evaporation is distributed as a negative accrual to ownership and debited to the rental links in proportion to their accrued carryover.

Each accrual link or storage right potentially has its own Rent Pool. All Rent Pool contributions from associated ownership links are summed for each accrual link, and all Rent Pool subscriptions from associated rental links are similarly summed. If the sum of contributions does not equal the sum of subscriptions, the larger of the two sums is proportionally reduced until they are equal, and the transfer of accrual credit is made. Notice again that rental links (i.e., the links with negative *Rent Pool Limits*) are treated much like ownership links except they do not actually own the storage right.

Water Service Contracts. Water service contracts are a different system of storage water administration, and can also be modeled using the *Rent Pool* capabilities. Under water service contracts, a water user agrees to pay for water delivered up to a certain contract amount, where this amount is a certain percentage of the reservoir fill each year. In this case, storage ownership is not an account that carries water over from year to year as in the previous example. Rather, the reservoir owner is represented as a demand node with an ownership link, and each year this owner *rents* the entire storage space to the individual water users as a percentage of the reservoir fill, thus simulating the service contract agreements.

Fig. 52 shows an example network for demonstrating the use of Rent Pool for Water Service Contract agreements. The demand **Bureau** represents the owner of the reservoir named **StorageRight.** The demand **TwoThirds** is a water user who has contracted for two-thirds of the available storage in the reservoir, whereas water user **OneThird** has contracted for one-third of the space. The storage ownership link **Divert_Bureau** shows an *Ownership Amount* of 300, which is the total available space for all the service

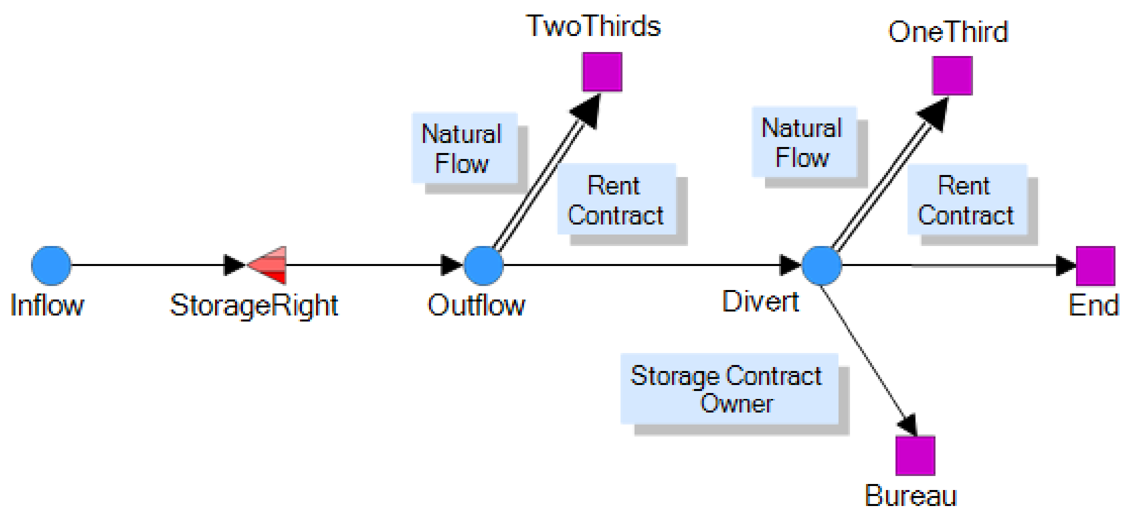
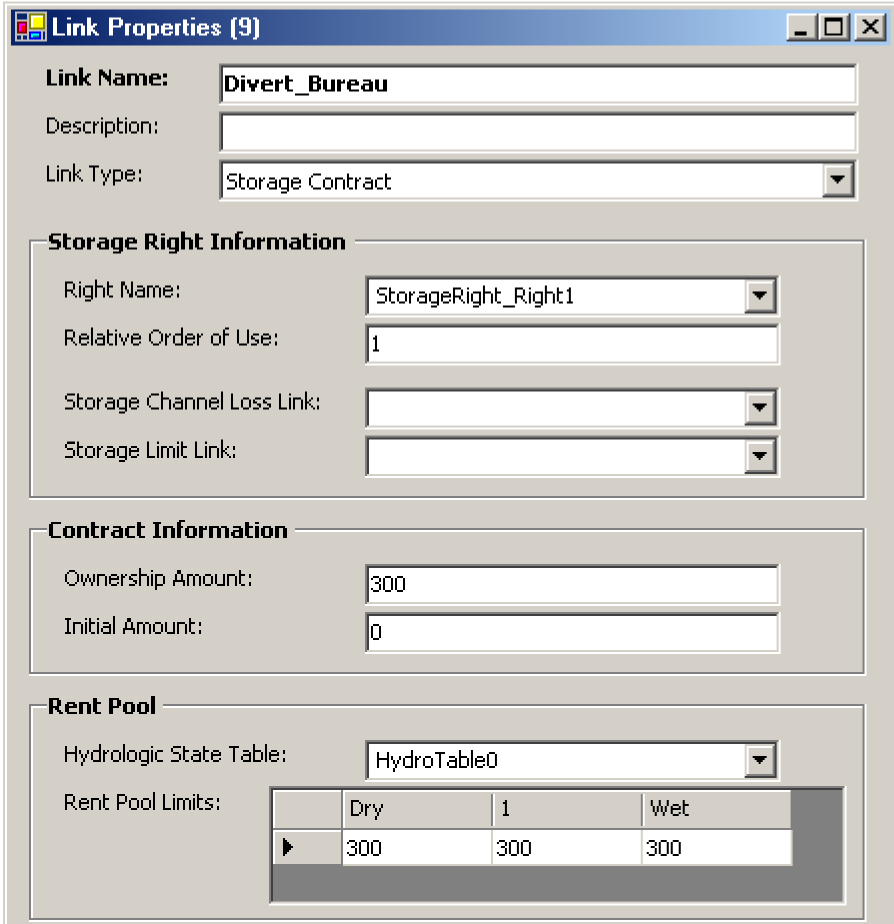
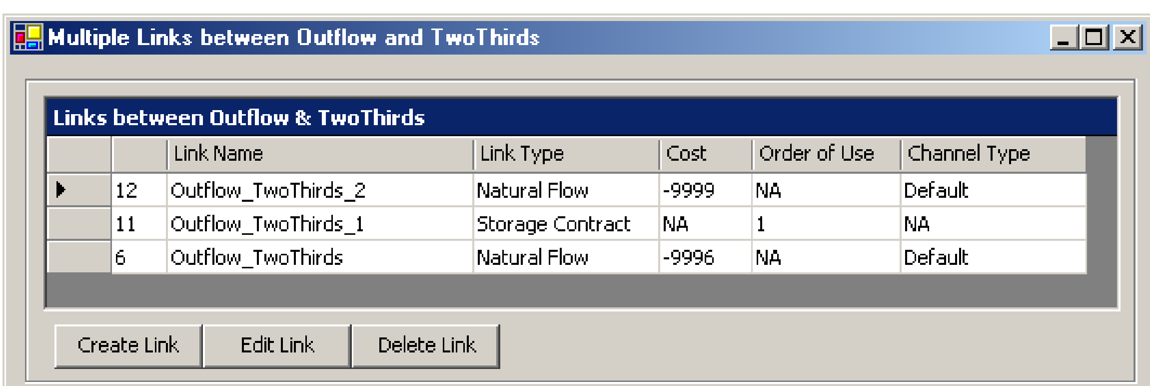


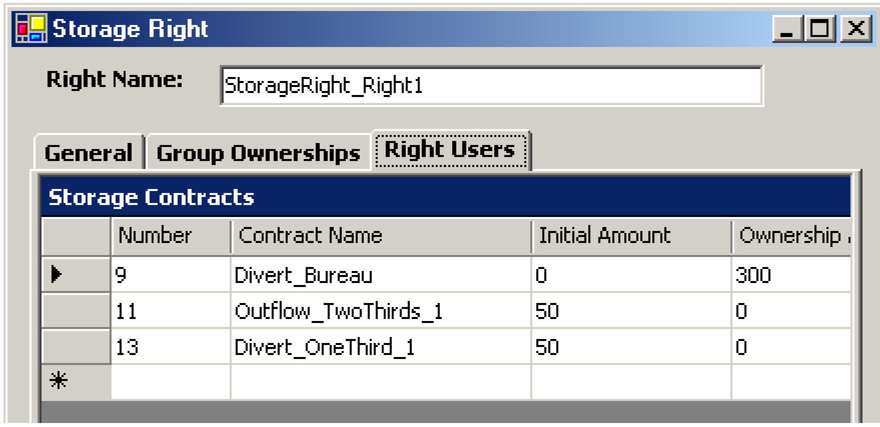
Fig. 52. Example network illustrating Water Service Contracts using the Rent Pool.

contracts. Notice that the *Rent Pool Limits* are set to 300 for all Hydrologic States, representing the amount that **Bureau** is contributing to the Water Service Contracts.



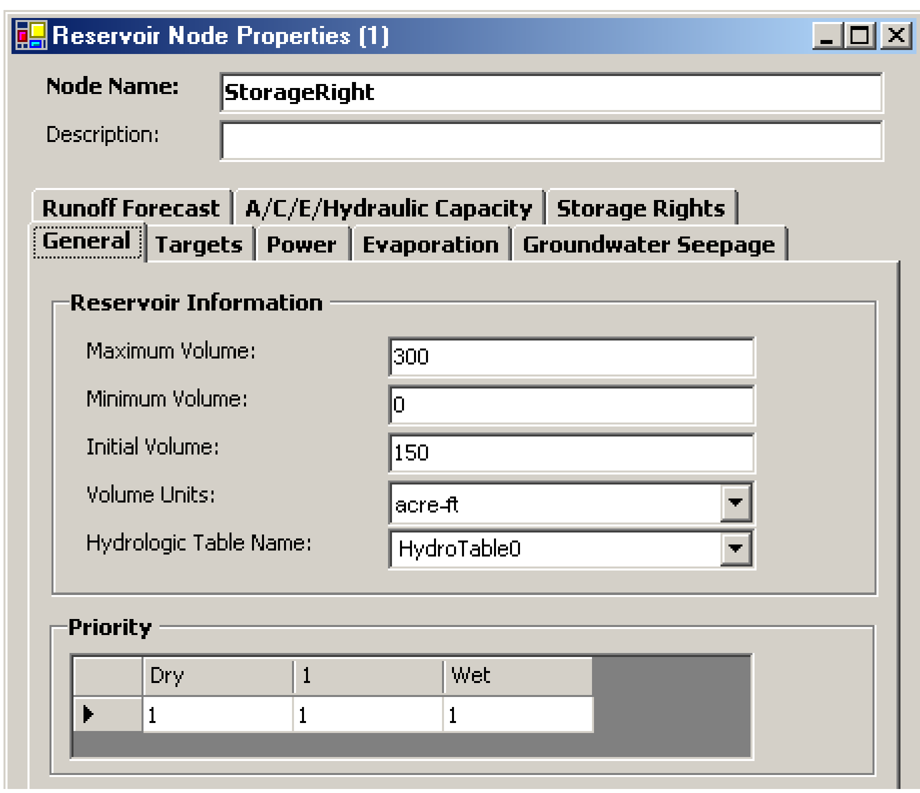
As seen here, demand **TwoThirds** has two Natural Flow rights, plus a *Storage Contract* link representing the Water Service Contract with **Bureau**. The Rent Pool Limits are set to -200, representing that demand **TwoThirds** has contracted for 2/3 of the total available space in **StorageRight**. The *Ownership Amount* is set to 0 in this case, since **Bureau** actually owns the reservoir **StorageRight**, but has agreed to enter into a contract that allows **TwoThirds** to utilize a portion of the available storage. The *Initial Amount* which is set to 50 represents a carryover from previous periods that **TwoThirds** has

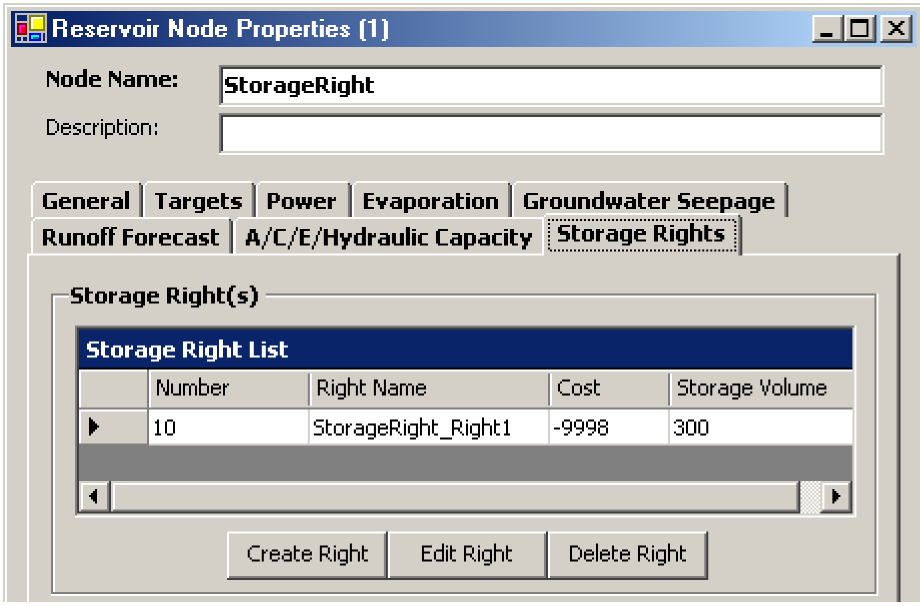




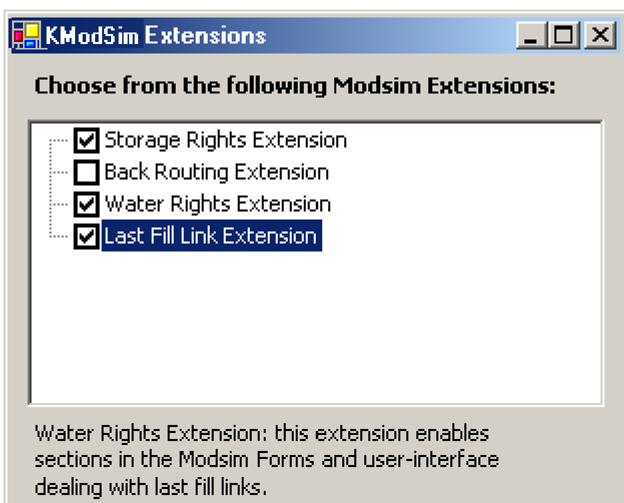
already utilized. Similar constructs are set up for the demand **OneThird**, with *Rent Pool Limits* set to -100 representing a contract for 1/3 of the available storage. Each year at the specified time step (**Network Settings** > **Storage Allocation Logic** > **Rent Pool Dates**),water accrued to the **Bureau** storage account is credited to these two links on a two-thirds and one-third proportion.

Notice that the total storage accounts available for Water Service Contracts cannot exceed the physical capacity of the reservoir, which is also 300 in this example. Clicking the *Storage Rights* tab on the **Reservoir Node Properties** form for the **StorageRight** reservoir displays the *Storage Right List*. Clicking *Edit Right* reveals both of the Water Service Contracts, as well as the storage ownership of **Bureau**.





Last Fill. Last-fill logic is related to the Rent Pool, and is activated by clicking **MODSIM > Extensions** and checking the box next to *Last Fill Link Extension*. This provides an administrative rule that alters the refill priority of rent water space that is used for specific purposes such as flow augmentation for endangered species, and other instream flow uses. The so-called *Last Fill* rule gives a junior priority to the space from which this last fill rent water is debited. Once this Extension is activated, if the rent water to be contributed or rented is subjected to this rule, a new *Last Fill Rule* check box is created in the **Link Properties** form for the storage contract link representing either Rent Pool contribution or subscription. Clicking the check box results in relegating the Rent Pool to Last Fill or junior priority status. Otherwise, the rent water space retains its original priority.



IX. MODSIM OUTPUT PROCESSING AND CUSTOMIZATION

A. Graphical Output Options

Selecting **MODSIM > Output Control** opens the tabbed form shown in Fig. 53 providing an extensive variety of graphical and text output options for any combinations of network objects and output data types. In addition, clicking the **Selective Output** tab

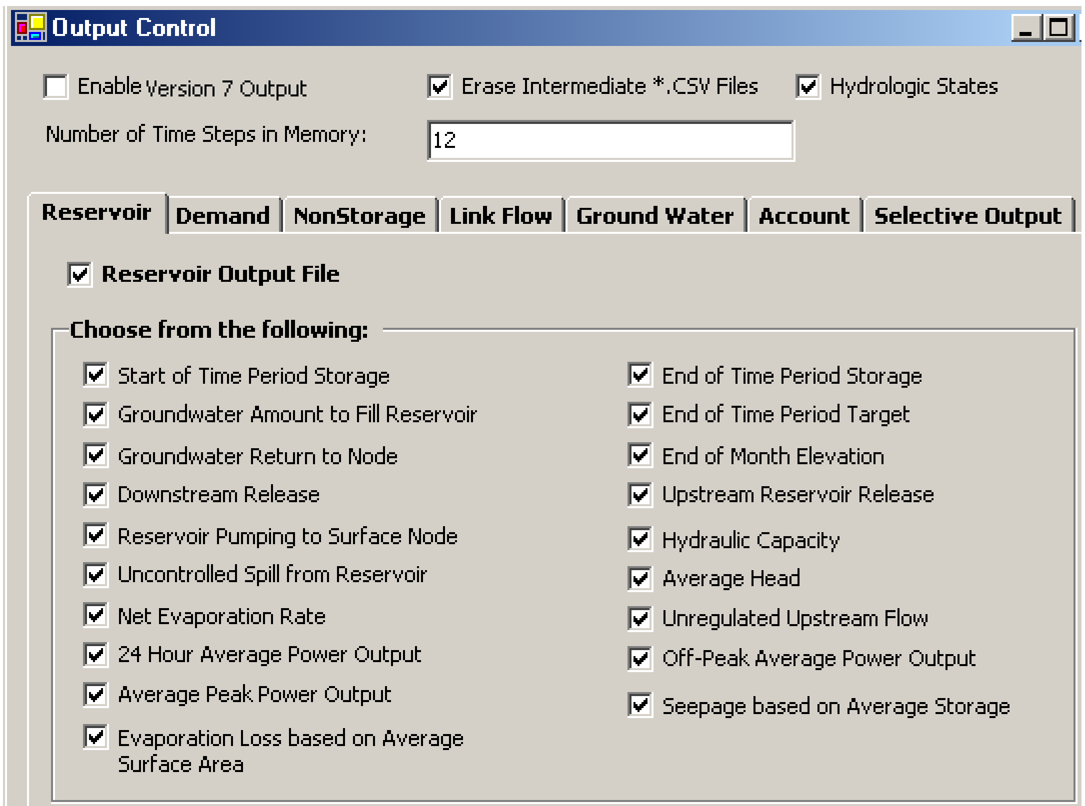


Fig. 53. Output Control form for selecting variables written to results files.

opens the form shown in Fig. 54 where users can select specific nodes and links to be included in the output files. This is useful for large networks in order to limit the size of output files to only the information needed by the user for a particular study.

All MODSIM simulation output is stored in MS Access *.mdb files, which can be directly opened by users if desired. However, MODSIM provides the capability of spatial selection of node and link objects for convenient graphical output display. After a MODSIM run is successfully executed, *right-button mouse click* on any node or link opens the context menu shown in Fig. 55, 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 for several MODSIM objects on the same

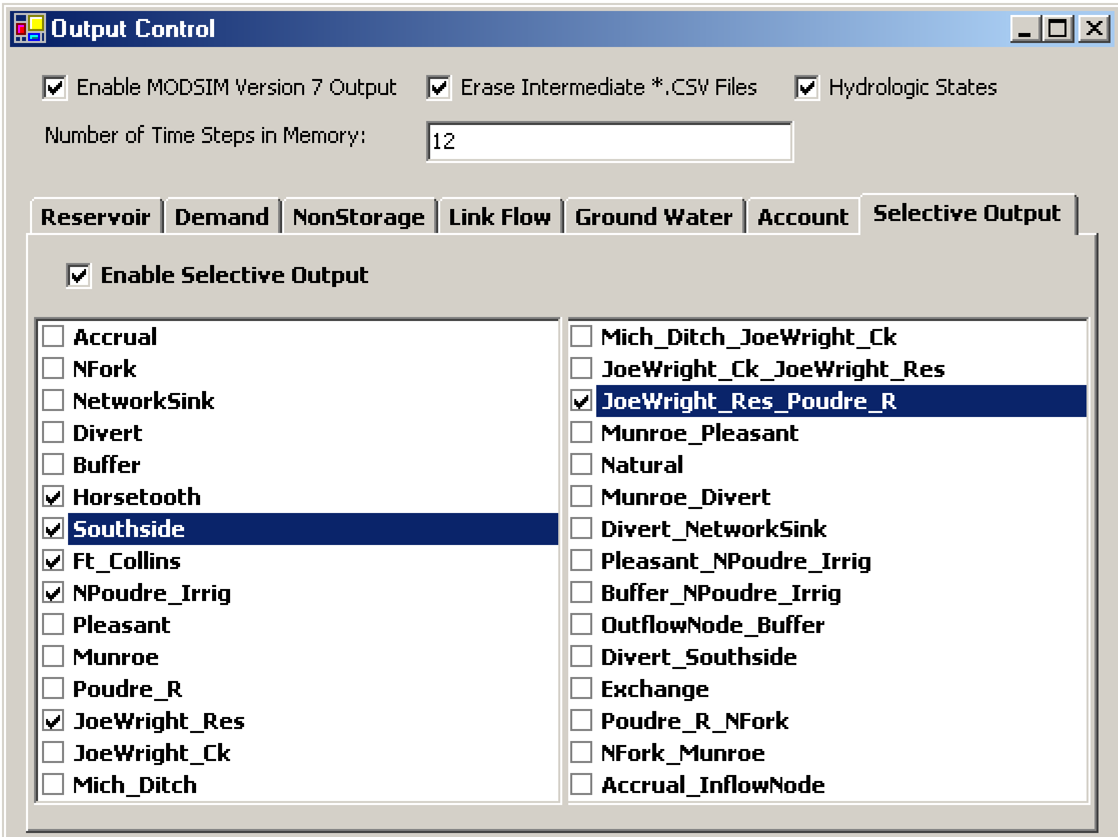


Fig. 54. Selecting desired MODSIM objects for output.

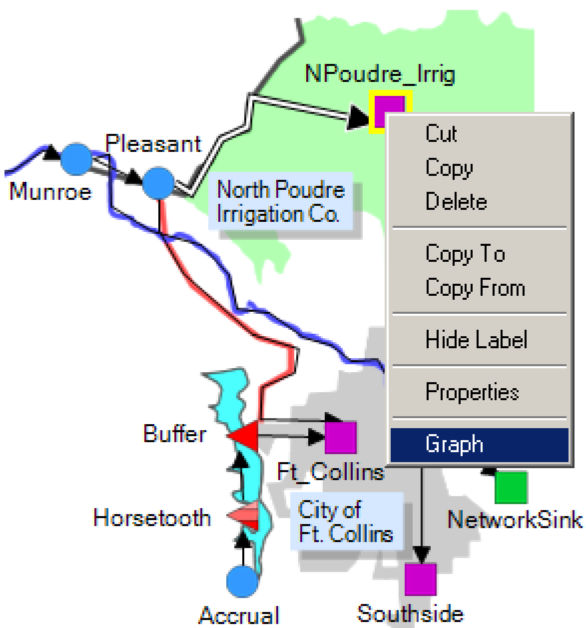
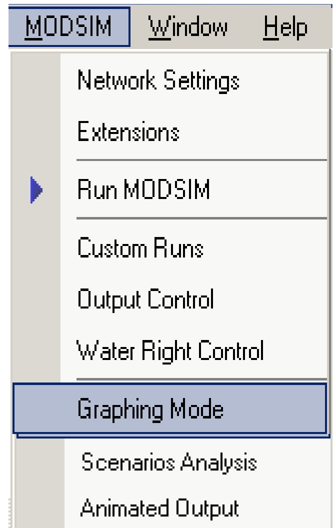


Fig. 55. Spatial selection of MODSIM objects for graphical output display.

graph. Generally, only similar MODSIM node or link types should be selected for simultaneous display, such as demand nodes, reservoirs, or flow links.

Another option that facilitates rapid selection of several nodes or links for graphical output display is to activate **MODSIM > Graphing Mode** on the main toolbar. Once activated, *left-mouse click* on any object in the MODSIM network display area immediately opens the graphic al output form for that object, such as shown in Fig. 56. Users can select either Line or Bar plots, and then choose the desired output values for that object by clicking the associated checkboxes in the Table of Contents. A extensive selection of chart formatting options is available, including 3-dimensional plots. Plots can be exported as image files, or the data can be exported to MS Excel for further plotting and analysis. Selecting the DATA tab in the Output Display gives tabular output results with detailed numerical values of simulation results corresponding to output *.mdb files stored in MS Access database files.



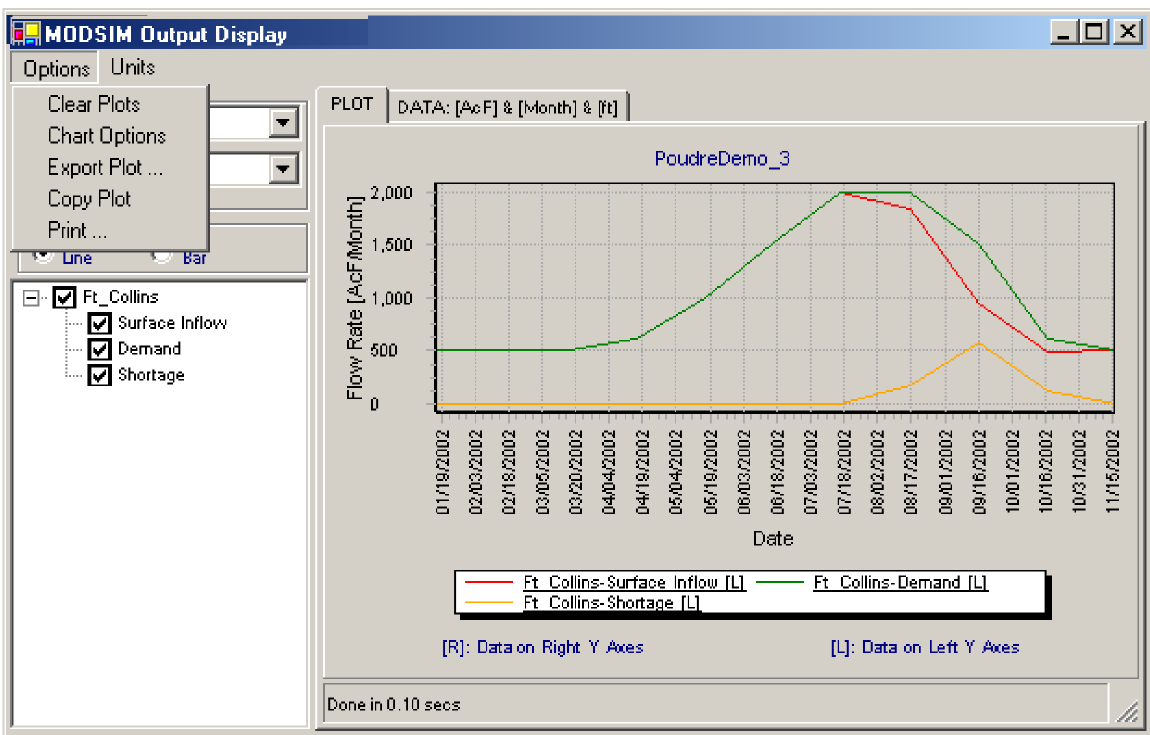


Fig. 56. Graphical output display for selected MODSIM object.

Selection of reservoir objects for output display results in plots with Left and Right Y axes displaying flow rate and storage volume, respectively, as seen in Figure 57. Users can select any desired units for output display. As shown in Figure 58, selection of several MODSIM objects of the same type (e.g., demand nodes, links, or reservoirs) allows comparative display of results in the same graphical plot.

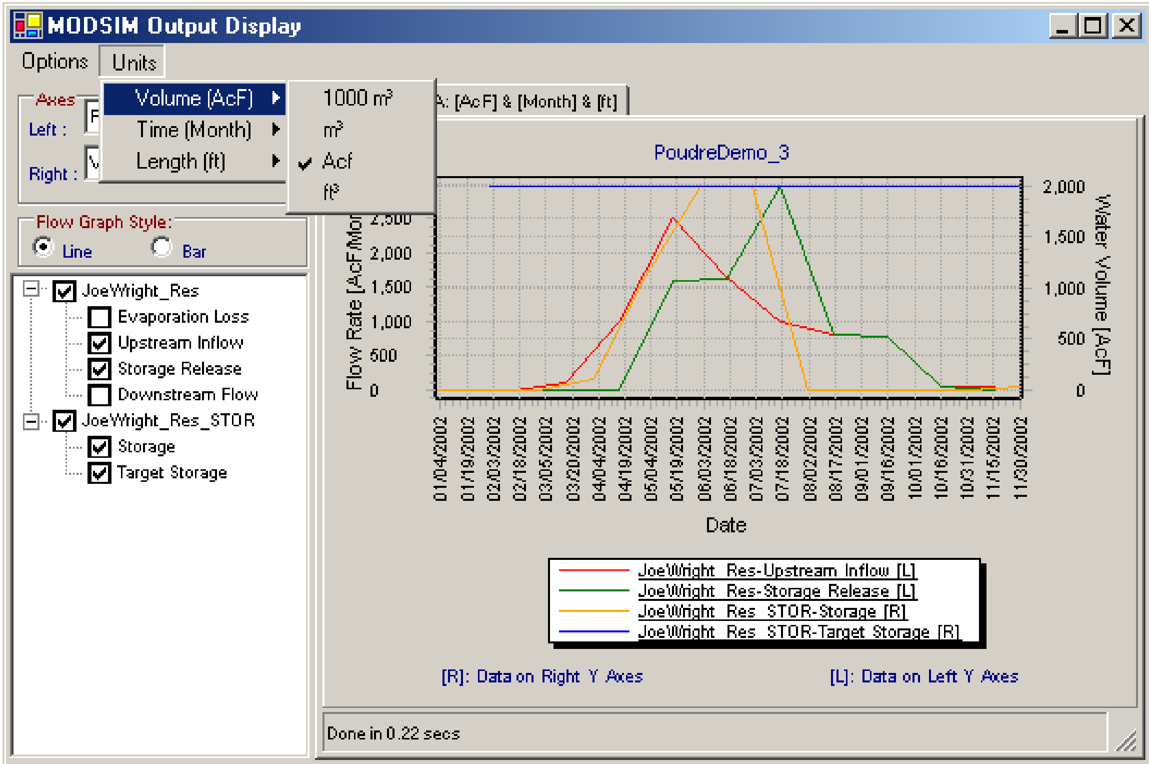


Fig. 57. Left and Right axis output displays for Reservoir nodes.

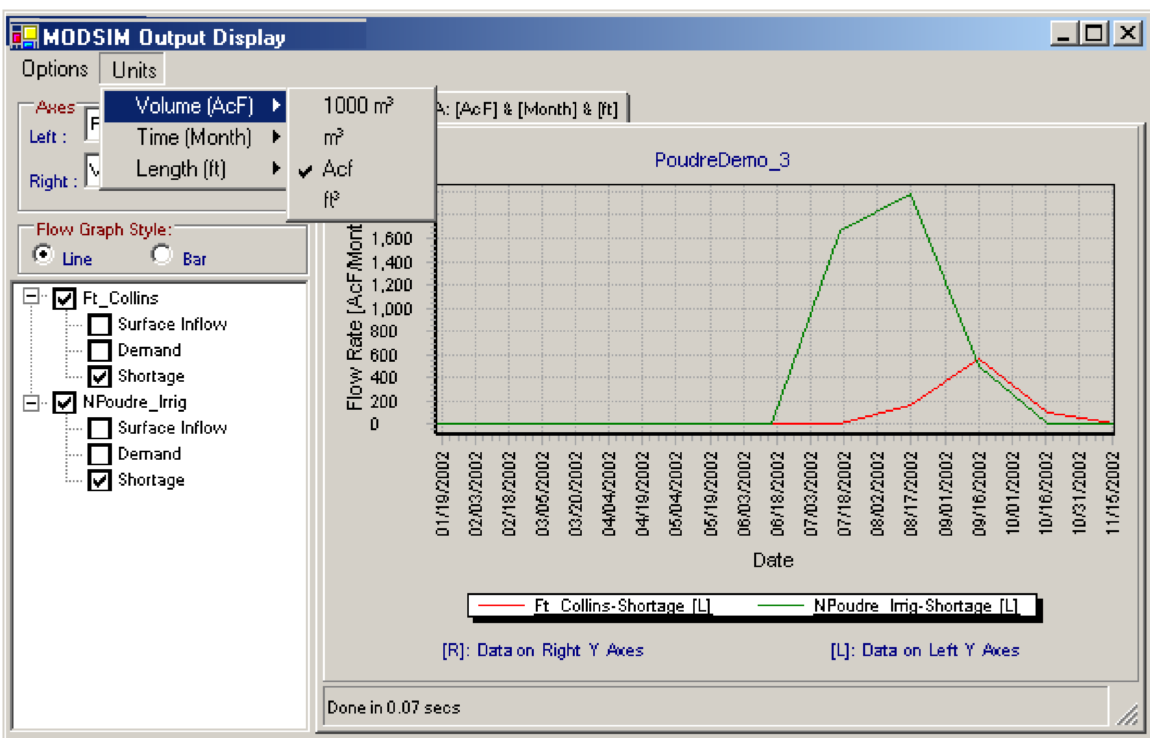
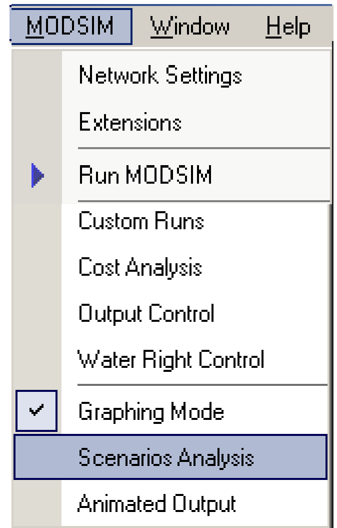


Fig. 58. Comparative graphical output display for several selected MODSIM objects.

B. Scenario Analysis and Flow Duration Curves

Activation of the **MODSIM > Scenarios Analysis** tool allows several networks representing alternative planning and management scenarios to be opened in the MODSIM interface simultaneously for comparison of results, including probabilistic flow duration curves and various statistical measures including reliability, resiliency, and vulnerability. Figure 59 shows a comparative analysis of probability exceedence curves on reservoir storage levels under two difference scenarios for augmenting instream flow requirements a downstream locations designated as critical habitat for endangered species. This is a useful tool for comparing the results of long-term Monte Carlo analysis on various scenarios. More detailed statistical information is also available to the user.



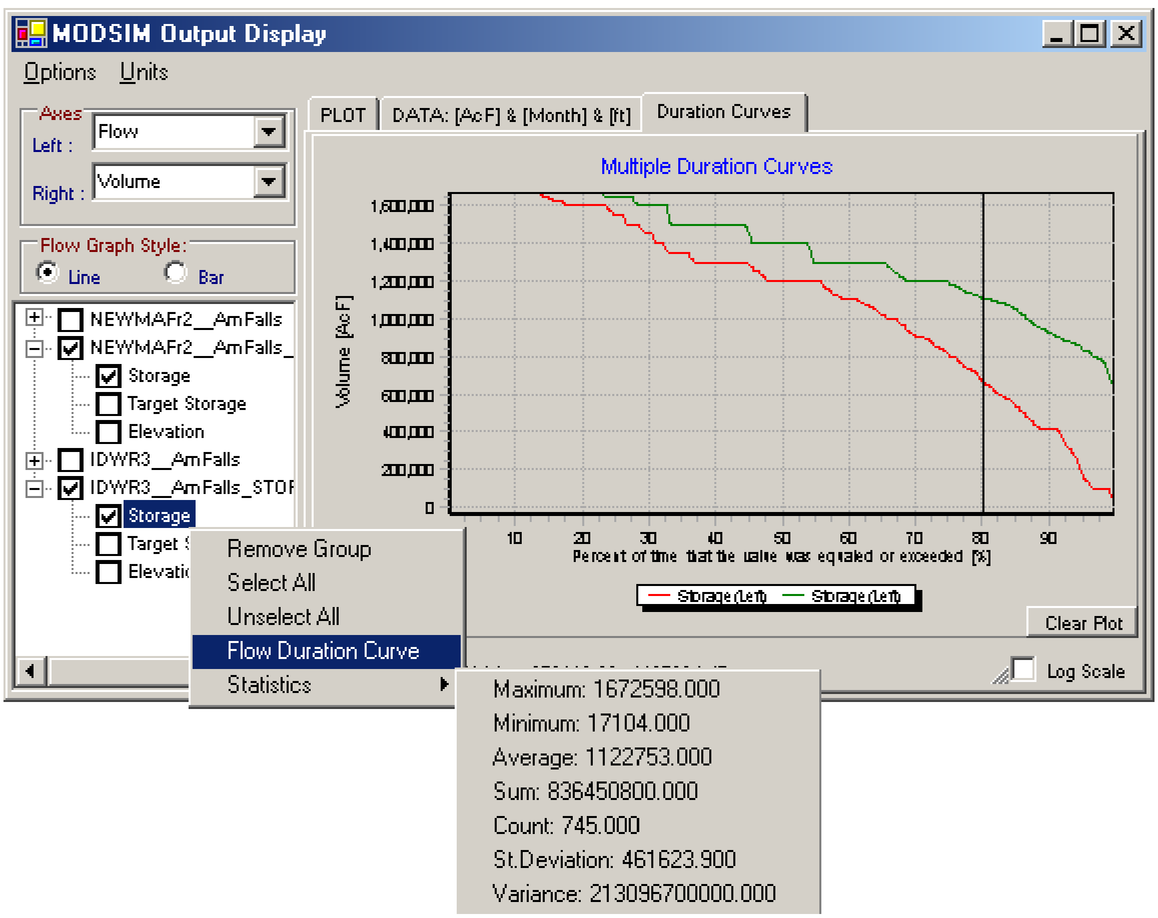
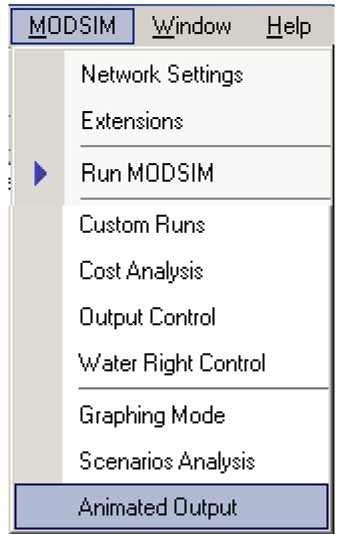
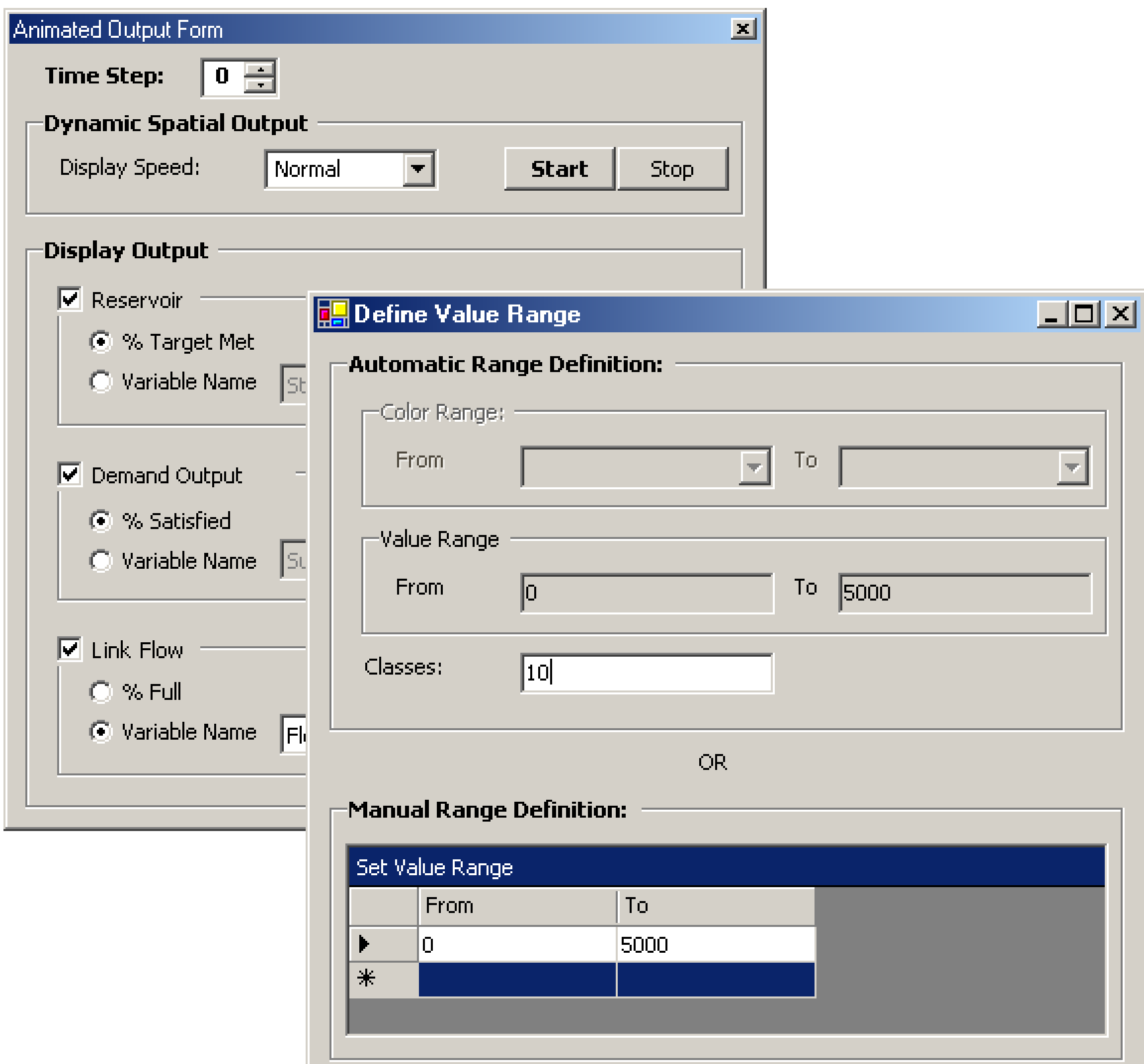


Fig. 59. Application of **Scenarios Analysis** tool for comparative evaluation of probability exceedence curves.

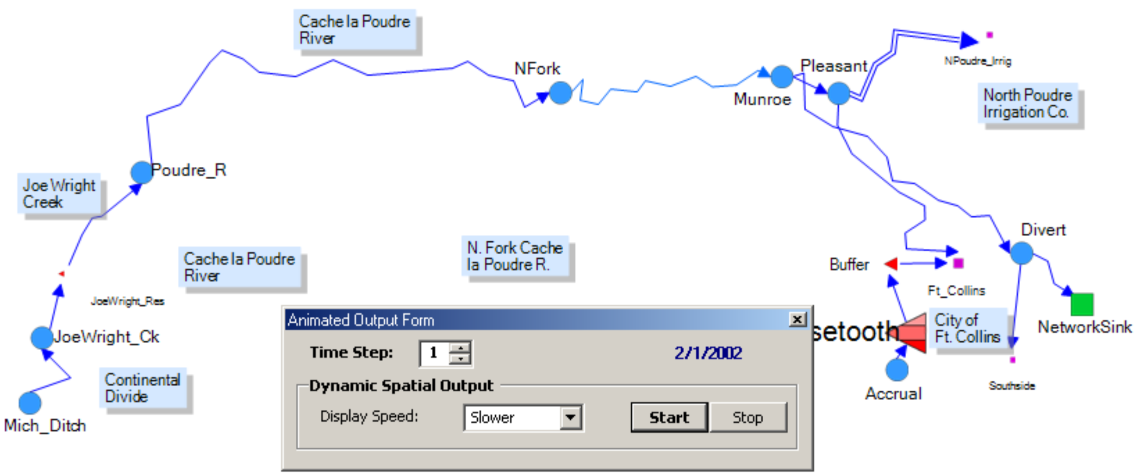
C. Animation of Simulation Output

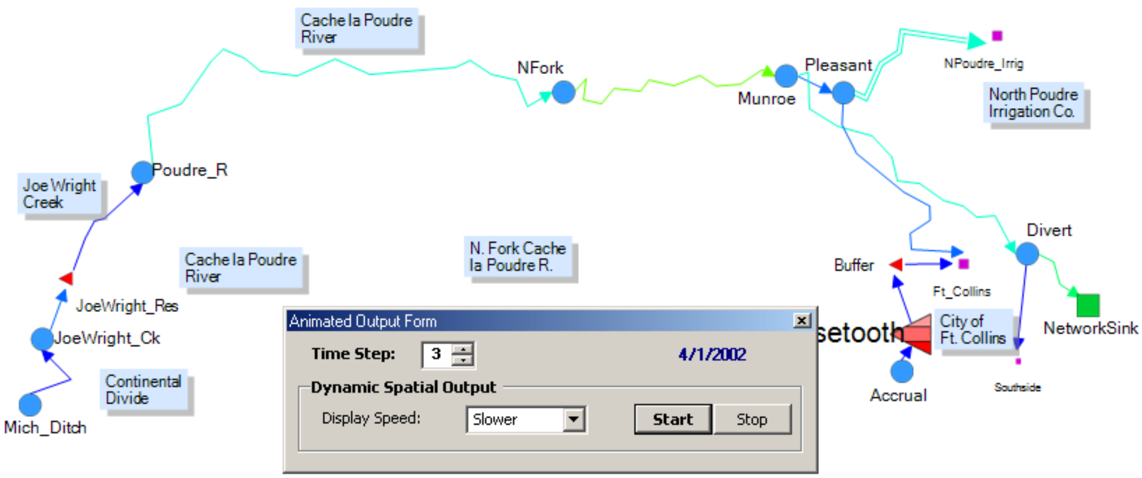
After successful solution of a MODSIM network, results can be presented in an animated display. The user can zoom in or out of the network display and focus on any desired portion of the network. Selecting **MODSIM > Animated Output** results in display of the **Animated Output Form**. The user can select one of three display speeds: *Slower*, *Normal*, or *Faster*. The reservoir and demand node icons dynamically change in size in proportion to either *% Target Met* or the magnitude of a selected variable associated with that object. Clicking the **Set Value Range** button displays the **Automatic Range Definition** form allowing users to specify the number of discrete classes that the **Value Range** for that variable is divided into. Rather than changing size, link flows are represented by changing colors within a desired color range and palette corresponding to % full or flow magnitudes.

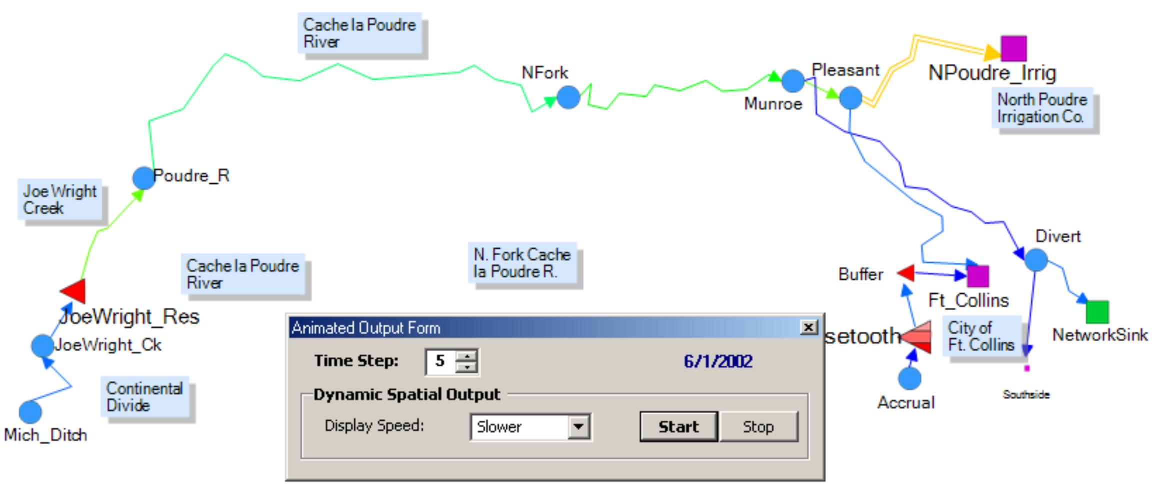




Shown below is a sequence of animations of the simulation results for a network showing reservoir and demand icons changing in size in proportion to storage and flow magnitudes, respectively, as well as link colors changing in accordance with flow magnitudes in those links. The animation continues to cycle through the time steps until the Stop button is clicked and the network display is reset to the original display.







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