Chapter 7

How To Use AQUARIUS

This chapter describes how to use AQUARIUS including how to: 1) build a flow network using the graphical user interface, 2) enter the necessary physical and economic data, 3) solve the water allocation problem, and 4) view model outputs. We assume that the user is familiar with basic procedures for running applications in a Windows environment such as choosing commands and resizing windows.

System Requirements

AQUARIUS requires an IBM-compatible personal computer with a Pentium-type processor and a 32-bit operating system (i.e., Microsoft Windows 98, NT, or 2000). Enhanced performance is attained using a system with high number crunching capabilities.

Exploring the Network Worksheet Screen

As described in Chapter 6, AQUARIUS was written using an object-oriented programming language. Each water system component is an object of the model, and each tool is a function that operates on an object. Although the object terminology is not repeated in this chapter, remember that the object structure of the model is what allows users to easily create a unique flow network composed of a set of water system components (WSC).

Network Worksheet (NWS) Screen

Once the AQUARIUS software is loaded in the computer, the application is launched by double-clicking the AQUARIUS icon. Initially a shortened menu selection is displayed with options for creating a new flow network or for opening an existing one by selecting the File menu. Then, the AQUARIUS screen and NWS appear (figure 7.1).

The NWS can be resized and scrolled. Several flow networks can be displayed simultaneously, although only one NWS is ever active. The title bar at the top of the NWS indicates the name of the flow network, which should have the file extension ".nwk". The menu bar at the top of the screen provides access to the various AQUARIUS commands. The two palettes at the sides of the screen contain the WSC (right side) and tools (left side) used to create the flow networks, as described later. At the bottom of the screen is the status line, which provides information on the currently selected object or procedure.

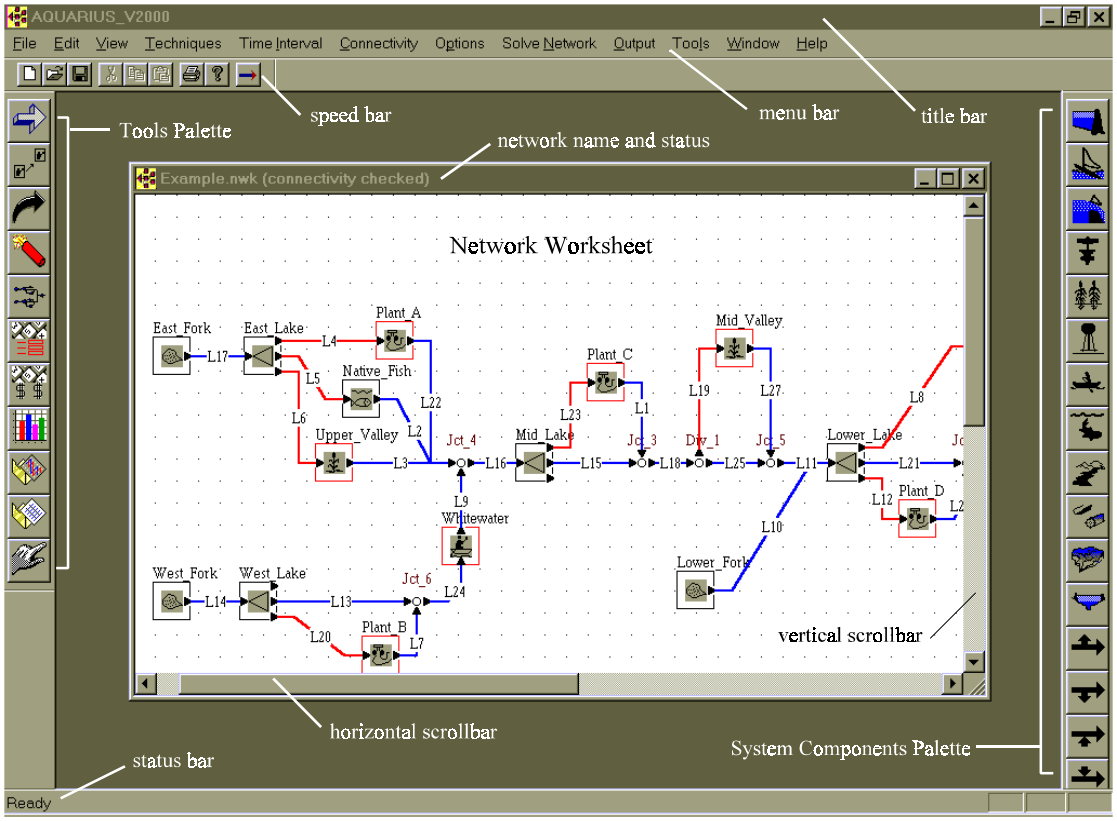


Figure 7.1 AQUARIUS network worksheet screen.

Menu Bar

Pull-down menus are arranged at the top of the screen as shown in figure 7.1. Each menu has sub-menus that allow the user to access the functions available in the model once a NWS is loaded. The complete layout of the pull-down menu bar is in figure 7.2. The command functions are explained throughout this chapter.

Water System Components (WSC) Palette

The WSC that make up a flow network are a series of nodes and links. All WSC are in a palette that is automatically displayed on the right side of the screen. The user can move the WSC palette any place on the screen including the four boundaries. The WSC palette can be removed from the screen by disabling the palette from the View menu. Choosing the WSC palette again returns it to its default position. The icons, names, and functions of the WSC are in table 7.1.

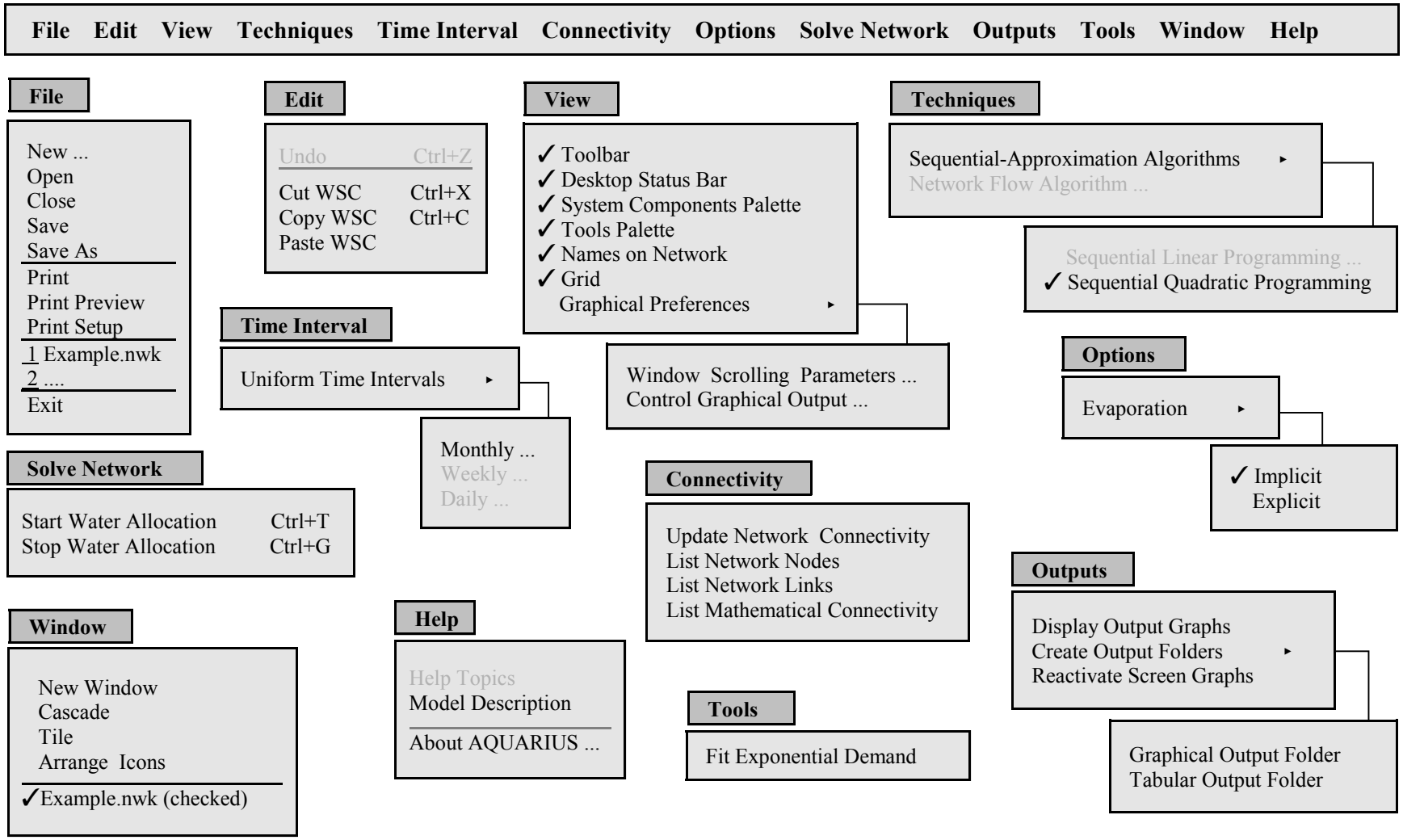


Figure 7.2 AQUARIUS pull-down menus (V2000).

Table 7.1 The water system components palette.

Button	Name and function
	Reservoir.. creates a water storage capacity for flow regulation.
	Reservoir Recreation.. creates a reservoir with water recreation activities.
	Spill Controller.. creates an object (spillway) that helps minimize reservoir spillages.
	Hydropower.. creates a powerplant for hydroelectric generation.
	Irrigation.. creates an offstream demand area of agricultural water.
	Municipal and Industrial.. creates an offstream demand area for urban and industrial water.
	Instream Recreation.. creates a river reach with water based recreation activities.
	Instream Flow Protection.. creates a river reach designated for fish habitat protection.
	River Reach.. creates a natural channel reach to convey flow between system components.
	Canal/Pipeline.. creates a flow conveyance structure such as a canal or pipeline.
	Flow Basin.. creates a water source area (basin) contributing uncontrolled flows.
	Flood Control [inactive].. creates a river reach with structural measures for flood control purposes.
	Left-bank Diversion.. creates a diversion point for diverting water over the left-bank.
	Right-bank Diversion.. creates a diversion point for diverting water over the right-bank.
	Left-bank Junction.. creates an inflow point to the waterway from its left-bank.
	Right-bank Junction.. creates an inflow point to the waterway from its right-bank.

Tools Palette

The tools palette gives quick access to a group of functions that operate the WSC. All tools are in a palette that is automatically displayed on the left side of the screen. The user can move the tools palette to any of the four sides of the screen. The tools palette can be removed from the screen by disabling tools palette from the View menu. Choosing tools palette again returns it to its default position. The icons, names, and functions of the tools are in table 7.2.

Table 7.2 The tools palette.

Button	Name and function
	Select.. selects one or more system components from a flow network.
	Move.. moves a system component within the network worksheet.
	Rotate.. rotates the direction of flow in a system component.
	Delete.. deletes a system component from the network worksheet.
	Physical Connectivity.. displays categories of in/outflows from a system component.
	Physical Input.. accesses the physical data structure of a system component.
	Economic Input.. accesses the economic data structure of a system component.
	Output Graph.. accesses the list of output variables of a system component.
	Graphical Folder.. opens a folder that creates a list of variables for output in graphical format.
	Tabular Folder.. opens a folder that creates a list of variables for output in tabular format (ASCII).
	Select Output Variables.. moves the output variables into the *Graphical /Tabular Folder.*

Note: icons in version 2000 look different than those shown in Table 7.2

Creating a Flow Network

The user interacts with the model through a graphical user interface to create a flow network. The graphical user interface consists of the four elements of the model introduced earlier: 1) the network worksheet (NWS), 2) the menus, 2) the water system components (WSC) palette, and 4) the tools palette.

In the NWS, each system component corresponds to a graphical node or link of the flow network. The components are represented by icons in the WSC palette, based on a pictorial representation of the component's function. By selecting (left clicking) an icon from the WSC palette and then left clicking again in the NWS, the model creates an instance of the component. In this manner, all the necessary components that simulate the topology of the actual river system are created.

To assemble a flow network, place two or more nodes (water sources, reservoirs, powerplants, demand areas, diversions, or junctions) in the NWS. Next, link the nodes using river reaches and canal/pipelines, also selected from the WSC palette. Once a link is selected, place it in the NWS by clicking first on an outgoing terminal of the upstream node and then on an incoming terminal of the downstream node, always in that order. Additional nodes and links can be added to a network, but links can only be placed between existing nodes.

There is no limit to the number of components that can be added to a network, but doing so increases the mathematical dimension of the water allocation problem and the computation time needed to find the optimal solution (see reference to computation times at the end of Chapter 8). In placing links, the model prevents most absurd connections such as routing water released from a reservoir back as an inflow to the same reservoir. Moreover, the model will automatically disallow connections that are hydraulically unsound or not allowed by the model.

Components can be moved anywhere in the NWS by clicking the *Move* button from the tools palette, clicking on the component, and dragging and dropping it to its new position. A component can be removed from the NWS by clicking the *Delete* button of the tools palette and then clicking on the component in the NWS. *Delete* removes the icon from the screen and eliminates that instance of the component from the model.

The creation and alteration of flow networks is expedited by copying and inserting portions of an existing network onto the same or a new NWS. To do this, click the *Select* button of the tools palette and select the part of the existing network to copy to the Windows clipboard. Select the desired part by dragging a rubber-band box around it. The starting point is the upper-left corner of the box, which is anchored by left-clicking at the location. The box is enlarged by dragging the pointer to its final position. The screen colors are reversed within the box (figure 7.3). To copy the information in the box into the Windows clipboard, choose *Copy WSC* under the Edit menu. To place the information from the clipboard to a NWS, select the command *Paste WSC* from the Edit menu and click at the desired location within the NWS. The *Paste WSC* command is available whenever the Windows clipboard has information that can be brought into a NWS.

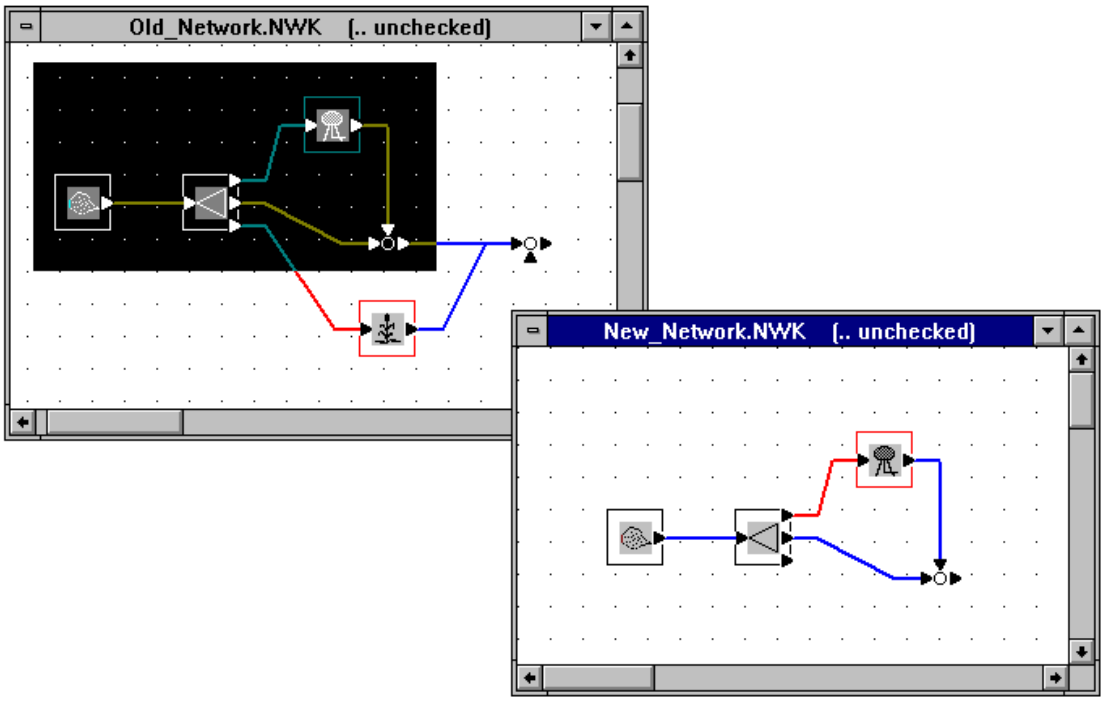


Figure 7.3 Copy and Paste of network components.

Because *Copy/Paste* creates new instances in the NWS of the components stored on the clipboard and duplicates their data structure, we call the duplicated objects clones. After pasting new components in a NWS, amend the data associated with the new components if they require different data from that brought in with the pasting operation. Information on the clipboard can be placed into numerous worksheet locations as long as it remains in the clipboard. *Copy/Paste* also provides the opportunity to build a library of individual components (e.g., reservoirs, irrigation areas) or small networks, which can be easily incorporated onto a NWS when necessary.

Entering Input Data

The model uses physical and economic groups of input data. The physical data consist largely of the dimensions and operational characteristics of the system components such as maximum reservoir storage capacity, powerplant efficiency, and the return flow coefficient from an irrigation zone. The economic data consist mainly of the demand functions of the various water uses competing for water within the river system. The input data entered for any system component is a property of the object, even when stored on disk for future use. When the

network is reloaded from the disk to the NWS, all data saved from the previous session for each component are retrieved in exactly the same form.

Physical Input Data

Physical data are entered into the model using a series of dialog boxes specifically designed for each system component. The data entry procedure is selected by clicking the *Physical Input* button from the tools palette and clicking the component of interest. A data entry dialog box opens with multiple tabs that group the input data by categories (figure 7.4). Table 7.3 lists the data required for each system component.

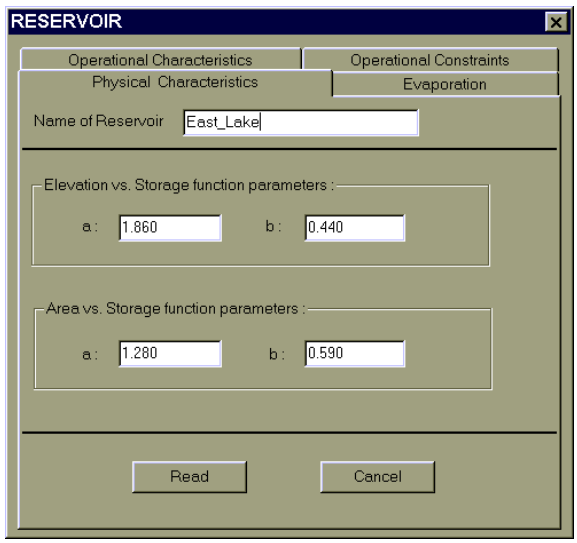


Figure 7.4 Physical data input dialog box for a reservoir.

Table 7.3 Physical inputs for the system components.

System component	Input data [units]	Reference
Reservoir (with and without lake recreation)	Physical Characteristics	
	Name of reservoir [alphanumeric]	
	Elevation vs. storage function, Parameters: c_1, d_1	Eq.(3.4a)
	Area vs. storage function: c_2, d_2	Eq.(3.4b)
	Evaporation	
	Seasonal evaporation rates [mm]	
	Operational Characteristics	Fig. 3.2
	Initial storage [Mcm]	
	Minimum storage [Mcm]	
	Maximum storage [Mcm]	
	Final storage [Mcm]	
	Operational Constraints (check-box)	Eq.(5.10-19)

	☒ Minimum storage	
	☒ Maximum storage	
	☒ Final storage	
	Spillway	Eq.(3.6)
	Spillway length [m]	
	Spillway crest elevation [m]	
	Spillway discharge coefficient	
	Parameters of the Discharge-Elevation Function:	
	Parameters of the Capacity-Surcharge Function:	
Hydropower	Physical Characteristics	
	Name of hydropower plant [alphanumeric]	
	Installed capacity [MW]	
	Design discharge [m^3/s]	
	Turbine-generator efficiency [-]	Eq.(3.8)
	Energy rate vs. storage function, Parameters: a_1, b_1	Eq.(4.1)
	Tailwater Elevation vs. Storage function:	
	Firm Energy:	
	Seasonal Pattern [GWh]	
	Maintenance Schedule	
	Index of availability of the hydropower units [-]	
	Maximum Release	
	Seasonal values [Mcm]	
	Minimum Release	
	Seasonal values [Mcm]	
	Operational Constraints (check-box)	
	☒ Minimum release	
	☒ Maximum release	
	☐ Firm energy	
Irrigation	Physical Characteristics	
	Name of irrigation area [alphanumeric]	
	Coefficient of return flow [-]	Fig.4.5
	Maximum Flow	
	Seasonal values [Mcm]	
	Minimum Flow	
	Seasonal values [Mcm]	
	Operational Constraints (check-box)	
	☐ Minimum flow	
	☐ Maximum flow	
	☐ Seasonal Pattern	
	☐ Annual firm water	
Municipal & Industrial	Physical Characteristics	
	Name of municipal and industrial area [alphanumeric]	
	Coefficient of return flow	Fig.4.6
	Maximum Flow	
	Seasonal values [Mcm]	
	Minimum Flow	
	Seasonal values [Mcm]	
	Operational Constraints (check-box)	
	☐ Minimum flow	

- ☐ Maximum flow
- ☐ Seasonal Pattern
- ☐ Annual firm water

Instream Recreation	Physical Characteristics Name of instream recreational area [alphanumeric] Maximum Flow Seasonal values [Mcm] Minimum Flow Seasonal values [Mcm] Operational Constraints (check-box) ☐ Minimum flow ☐ Maximum flow
Instream Flow Protection	Physical Characteristics Name of conservation area [alphanumeric] Maximum Flow Seasonal values [Mcm] Minimum Flow Seasonal values [Mcm] Operational Constraints (check-box) ☐ Minimum flow ☐ Maximum flow
Flood Control	(not implemented)
Natural Flow Basin	Physical Characteristics Name of river/basin [alphanumeric] Input file name [Path....]
River Reach	Physical Characteristics Name of river reach [alphanumeric] Connectivity, From: __ To: __ Description [alphanumeric] Length [m] Hydraulic Characteristics Maximum flow capacity [m^3/s] Flow velocity [m/s] Channel losses [l/km] Flow routing (check- box) Routing parameters: k, x
Canal/Pipeline	Physical Characteristics Name of river reach [alphanumeric] Description [alphanumeric] Length [m] Connectivity, From: __ To: __ Hydraulic Characteristics Maximum flow capacity [m^3/s] Flow velocity [m/s] Canal/pipe losses [l/km]

Diversion	Physical Characteristics ☐ Node water-balance (check-box)
Junction	(No input data required)

Note: an option is enabled when a check mark appears in the check box; disabled when the check box is empty.
Variables in shaded font are unavailable in version 2000.

Economic Input Data

The economic data are the parameters necessary to specify the demand curves (i.e., the marginal prices that users are willing to pay) for water during each season of the optimization horizon. The data entry procedure is selected by clicking the *Economic Input* button from the tools palette and clicking the object of interest. The user has the option to choose either exponential or constant prices, after which a data entry dialog box opens for user interaction (figure 7.5). Table 7.4 lists the economic data required for each competing water use.

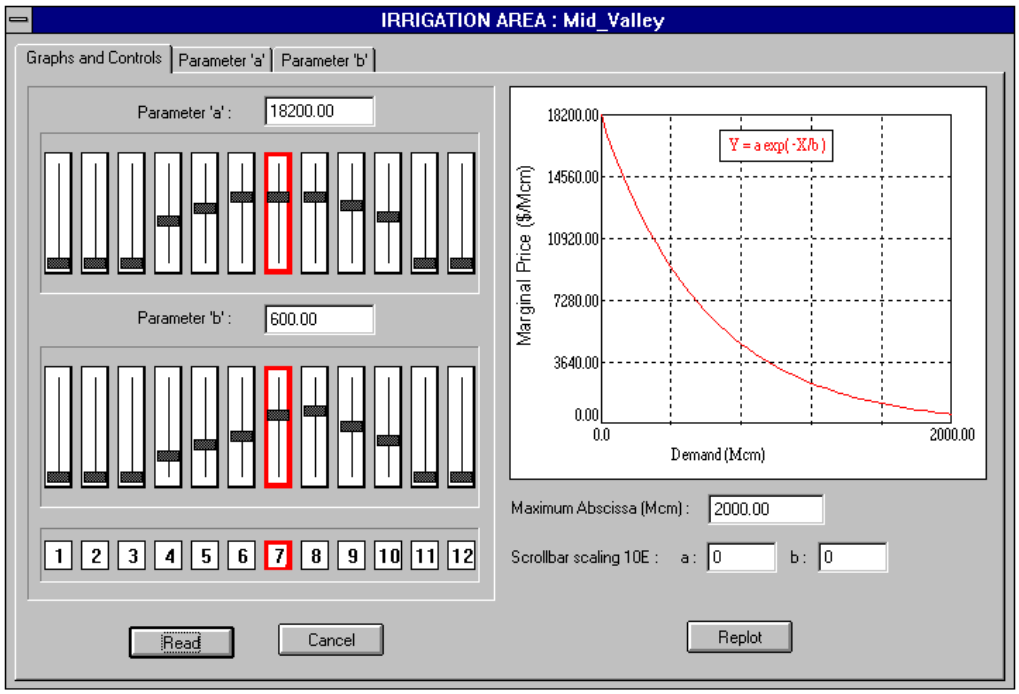


Figure 7.5 Economic data input dialog box for an irrigation area.

Table 7.4 Economic inputs for the system components.

System Component	Input Data [units]	Reference
Hydropower	Energy Generation Benefits Average energy price: P [$/MWh] Seasonal energy prices: P_s [$/MWh] Energy demand function; Parameters: a_2, b_2	Eq.(4.3)
Irrigation	Agricultural Benefits Seasonal demand function; Parameters: a_3, b_3	Eq.(4.15)
Municipal & Industrial	Urban and Industrial Water Supply Benefits Seasonal demand function; Parameters: a_4, b_4	Eq.(4.20)
Instream Recreation	Instream Recreation Benefits Seasonal demand function; Parameters: a_5, b_5	Eq.(4.25)
Reservoir Recreation	Lake Recreation Benefits Seasonal demand function, Parameters: a_6, b_6, c_6	Eq.(4.30)
System (whole network)	Present Worth Analysis Number of discounting periods Discounting rate [%] Price escalation rate { %] Value of the objective function expressed in: ☐ Thousands [$] ☒ Millions [$]	

Updating Network Connectivity

Once the flow network is assembled, the model conducts a series of validation steps before proceeding to solve the water allocation problem. These procedures are launched by choosing the command Update Network Connectivity from the Connectivity menu. Among the various validation steps, the model checks that:

- all WSCs are named;
- all WSCs that compete for water have marginal prices different from zero;
- water uses such as IRA, IFP and FCA are instream users;
- reservoirs have a waterway available for releasing uncontrolled spills; and
- component connections are hydraulically sound.

Warning messages are displayed for violations of preestablished network connectivity rules. If all steps are successfully completed, the network status changes from connectivity *..unchecked* to connectivity *..checked* on the title bar of the NWS.

System components competing for water are framed by a red line on the screen. Similarly, links conveying controlled flows (i.e., links leaving a node where a decision is made) are turned red. The number of sets of decision variables is equal to the number of red links. The WSC frame and the links turn red after updating network connectivity.

An additional operation performed during this stage is defining the hydraulic connectivity of the network objects. This information is used by the model to generate the mathematical connectivity of the system components based on the requirements of the optimization technique selected. Details on the mathematical connectivity of the system elements are in Chapter 6.

If Names on Network is chosen from the View menu, next to each component in the NWS the model displays the name assigned to the component by the user and the number assigned by the model to links (i.e., river reaches and conveyance structures) and to diversion and junction nodes. The user can also look at and print a table summarizing the network nodes (figure 7.6 top) and another one summarizing network links (figure 7.6 bottom). These tables are accessed by the commands List Network Nodes and List Network Links in the Connectivity menu.

Table of Nodes for: Example.nwk

No.	Name	Type	Price Function	Connections Upstream	Connections DownStream
1	Big_City	MUNICIPAL	Yes	Lower_Lake	_
2	East_Fork	NATURALFLOW	No	_	East_Lake
3	Plant_D	POWERPLANT_VH	Yes	Lower_Lake	Jct_3

Table of Links for: Example.nwk

File

No.	Name	From	To	Description
1	L1	Plant_A	Jct_5	routing
2	L2	East_Fork	East_Lake	natflow
3	L3	Plant_C	Jct_4	routing
4	L4	Div_2	Mid_Valley	decision
5	L5	Upper_Valley	Jct_5	return
6	L6	Lower_Lake	Plant_D	decision
7	L7	Native_Fish	Jct_5	routing
8	L8	Lower_Lake	Big_City	decision
9	L9	East_Lake	Plant_A	decision

Figure 7.6 Table of network nodes and connectivity links.

Selecting the Optimization Technique

AQUARIUS uses a sequential optimization technique, Sequential Quadratic Programming (SQP), for solving the water allocation problem. Details of the algorithm are in Chapter 5. The algorithm is selected from the Techniques menu. This command opens a dialog box containing a series of parameters, specified by the user, that control the sequential process and the accuracy of the computations (figure 7.7). Parameters are divided into two groups, those that control the sequential approximation algorithm, named *Sequences Parameters*, the purpose of each is:

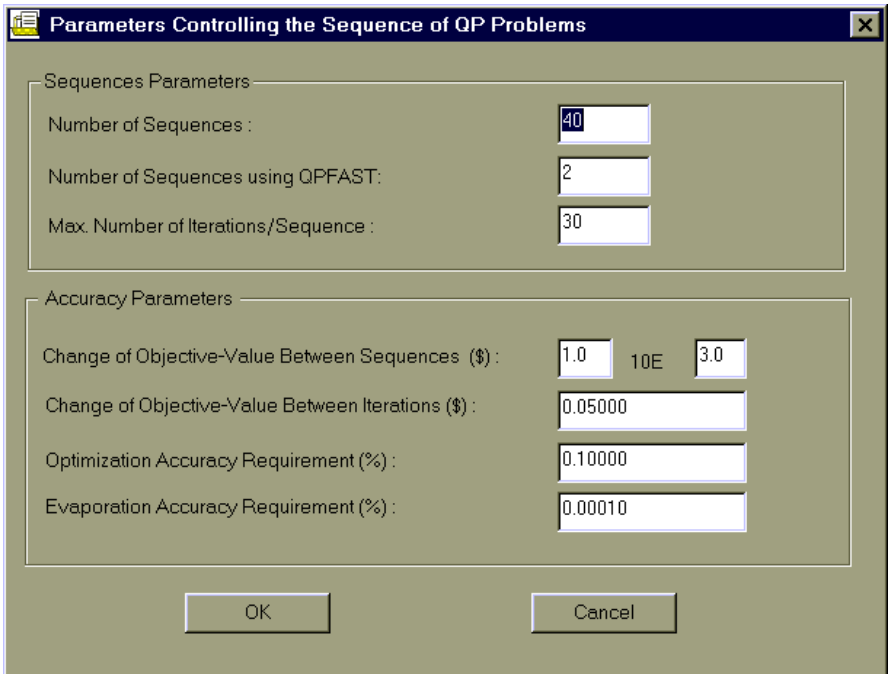


Figure 7.7 Control parameters dialog box.

Number of Sequences: this defines the maximum number of QP sequential problems to be solved (see Figure 5.1). The default for this parameter is 50, which is a reasonable number for a medium size networks as the one presented in Chapter 8.
Number of Sequences using QPFAST: after an initial feasible solution is found, a few number of sequences are specified to approximate the solution to a near-optimal level. The recommended value is between 1 and 5. The default value for any new run is set equal to 3.
Max. Number of Iterations per Sequence: this parameter is intrinsic to the general differential algorithm used by QPTHOR to solve the QP problem. The user should explore values ranging from 5 to 50 iterations per sequence. In general, the larger the value adopted, the smaller the number of sequences necessary to reach the optimal solution.

And the *Accuracy Parameters*, to control the accuracy of the calculations. The purpose of each parameter is:

Change of Objective-value between Sequences: is the main stop criterion. Five consecutive solutions (sequences) of the nonlinear problem with an objective function change less than the specified dollar amount will cause the application to stop ($1000 in the example).
Change of Objective-value Between Iterations: this is the stop criterion for each sequence of the differential algorithm (QPTHOR), similar to the criterion above ($0.05 in the example).
Computational Accuracy Requirement: used extensively during optimization. A quantity q is set equal to zero when its value is less than its order of magnitude $\bar{q}$ times a selected accuracy (e.g., $q < \Delta\,\bar{q},\ \Delta = 0.1$ in the example).
Computational Accuracy for Evaporation: this parameter is used during the reconciliation procedure implemented for the "Implicit" modeling of reservoir evaporation (0.0001 in the example).

The final solution to the water allocation problem found by the model is generally sensitive to the values assigned to the parameters listed above. The proper values for the parameters will depend on the topology of the network, the number of water users competing for water, and the length of the optimization horizon. Given the difficulty of preestablishing the proper value for all these parameters, the user should begin running the model with the default values and then experiment with different values for the parameters to find the most appropriate set of numbers for the problem at hand.

Specifying the Simulation Time Interval

The time interval for the analysis is specified by selecting the Uniform Time Intervals from the Time Interval menu. This opens a submenu for selecting the periodic time interval: *Monthly...*,

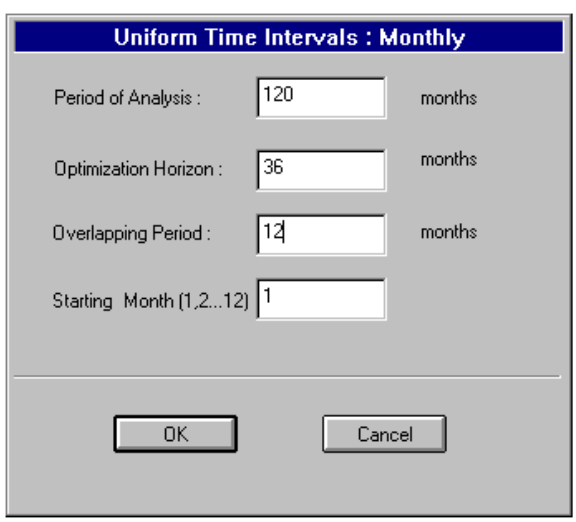


Figure 7.8 Period of analysis and optimization horizon dialog box.

Weekly..., Daily.... Once the periodic time interval is selected, a window opens to enter the four items listed in the dialog box in figure 7.8. Although the model was conceived to operate at any of the uniform time steps offered in the menu (monthly, weekly, daily), present limitations in the graphical user interfaces allow for only monthly time intervals.
The first entry in figure 7.8, Period of Analysis, specifies the length, in number of periods, of the whole segment of time for which the model will determine the system operation. Inflow data should be provided for at least the same segment of time. The next entry, Optimization Horizon, also in number of time periods, specifies how far into future the model should look to build the optimal operational policies. The optimization horizon defines the actual size of the optimization problem(s) being solved.

If the Optimization Horizon is set equal to the Period of Analysis (overlapping period = 0) , the quasi-continuous optimization scheme is disabled (see Chapter 5, Time Intervals of Analysis); hence, the optimal operational policies identified by the model will extend for the full number of periods indicated by the optimization horizon. However, when the period of analysis is longer than the optimization horizon, which enables the quasi-continuous optimization procedure, the user must also specify the number of Overlapping Periods. The model allows the user to prescribe any number of overlapping periods for monthly simulation.

The last input in the dialog box in figure 7.8, Starting Month, indicates the period within the annual cycle for the start of the system operation. For instance, 1 for January, 2 for February, . . 12 for December (for a monthly time step). In this manner, time series data, such as inflows, evaporation rates, etc., are properly considered.

Solving the Water Allocation Problem

Once the network is assembled, including input of all the physical and economic data, and the network connectivity is verified, AQUARIUS can find the optimal water allocation. This is accomplished by selecting the command Start Water Allocation from the Solve Network menu. The problem is solved in two steps. First, an initial feasible solution (IFS) to the water allocation problem must be found. The IFS that the model finds will generally be far from the optimal solution (see Chapter 5, Search for a Feasible Solution), but serves as the starting point for the sequential optimization procedure that follows. The IFS is obtained automatically by the model (the search for an IFS is invisible to the user), and only for a network in the *..checked* condition. By specifying zero (0) number of sequences, the user can make the model to stop after finding the IFS. The graphical output capabilities of the model, introduced next, can be used to render the state of the system that corresponds to the IFS found by the model.

The second step, actual optimization, consists of running an optimization algorithm to find the optimal solution of the water allocation problem. As explained in Chapter 5, sequential algorithms go through a succession of quadratic approximations of the nonlinear global objective function until the optimal solution is reached. The maximum number of QP sequences allowed is

indicated in the corresponding dialog box (figure 7.7). As the solutions of the QP problems progress, the status bar at the bottom of the screen displays the sequence number. Once the optimal solution is found, or the maximum number of sequences is reached, the optimization stops (indicated in the status bar). The sequential optimization process can be interrupted by selecting Stop Water Allocation from the Solve Network menu. The user can track the sequential changes in system state and decision variables during the optimization by using the graphical output capabilities presented next.

Graphical and Tabular Output

Flow networks generally contain many state, decision, and economic variables that an analyst should consider. AQUARIUS facilitates the interpretation and analysis of all information through readily accessible graphical and tabular output display formats. The user can display output variables on the screen by selecting Display Output Graphs from the Outputs Menu or by pressing the corresponding icon in the tools palette and clicking on the component of interest in the NWS. This opens a dialog box that lists all physical and economic output variables available for that component. Figure 7.9 shows a dialog box for a reservoir. A graph window is created when a check mark is inserted (enabled) in the corresponding check box and is deleted (disabled) when the check box is empty.

If instead of clicking on a WSC in the NWS, the user clicks any place in the worksheet, a graph window opens showing the evolution of the total-objective function value as the sequential algorithm (SQP) completes optimization. This is possible because the flow network as a whole is also an object (Chapter 6).

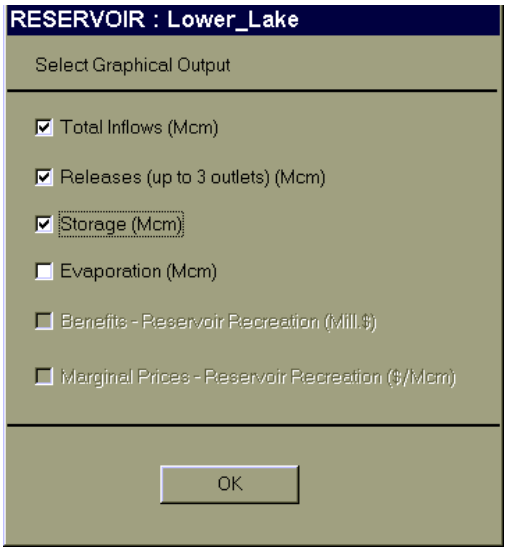


Figure 7.9 Selecting graphical display output variables for a reservoir.

Single-variable graph windows allow the user to visualize the sequential changes in the state, decision, and economic output variables as the system reaches its optimal state. Visualizing sequential changes is only possible if the output graph windows were opened either before launching optimization or during the optimization.

Several graph windows can be open simultaneously, the only limitation is the number of windows visible on the screen at one time. As they are opened, the graph windows appear on the screen in a cascade format. The user may choose Tile from the Window menu to display all graph windows at once. The model maintains a register of all graph windows opened during a working session. The same graph windows can be

reactivated any time by choosing Reactivate Output Graphs from the Outputs menu. The continuous refreshing of the graphical output windows after each sequence of optimization increases the execution time of the model. Table 7.5 presents the output variables available for graphical display, listed by type of water system component.

Table 7.5 Output variables for the water system components.

Reservoir and **Reservoir Recreation**
- ☐ Total Inflows [Mcm]
- ☐ Releases (up to 3 outlets) [Mcm]
- ☐ Storage [Mcm]
- ☐ Evaporation [Mcm]
- ☐ Benefits - Lake Recreation [Mill.$]
- ☐ Marginal Prices - Lake recreation [$/Mcm]

Hydropower
- ☐ Powerplant Flows [Mcm]
- ☐ Hydropower Generation [GWh]
- ☐ Benefits - Hydrogeneration [Mill.$]
- ☐ Marginal Prices - Hydrogeneration [$/Mcm]

Irrigation
- ☐ Allocated Flows [Mcm]
- ☐ Return Flows [Mcm]
- ☐ Benefits - Agricultural Use [Mill.$]
- ☐ Marginal Prices - Agricultural Use [$/Mcm]

Municipal & Industrial
- ☐ Allocated Flows [Mcm]
- ☐ Return Flows [Mcm]
- ☐ Benefits - Urban Use [Mill.$]
- ☐ Marginal Prices - Urban Use [$/Mcm]

Instream Recreation
- ☐ Instream Flows [Mcm]
- ☐ Benefits - Instream Use [Mill.$]
- ☐ Marginal Prices - Instream Use [$/Mcm]

Instream Flow Protection
- ☐ Instream Flows [Mcm]
- ☐ Ecological Index

Natural Flow Basin
- ☐ Natural Flows [Mcm]

Network
- ☐ Global Objective Function [Mill.$]
- ☐ Periodic Series of Benefits [Mill.$]

In addition to single-variable graphs, the user can create graphical and tabular outputs containing one or more physical or economic variables. This is useful for displaying, in the same graph, output variables of the same class generated at different locations in a flow network. For instance, the user may want to compare energy generated at different powerplants, instream versus offstream water allocations, or storage trajectories for all reservoirs. Similarly, this option can be used to generate tabular outputs (in ASCII format) that can be printed or automatically imported into an Excel spreadsheet. This is done by selecting Create Output Folders from the Outputs menu. This opens a submenu from which to choose either a Graphical or a Tabular Output Folder. Folders can also be opened from the tools palette. Both choices open a new window, the folder, that will list all output variables. Once the folder window is visible, the procedure for selecting the variables starts by clicking the *Select Output Variable* button of the tools palette and clicking the component of interest in the NWS. This opens another window that lists all output variables for that specific component (table 7.5 and figure 7.10). Select the output variables of interest by dragging each one from the Select Output Variable window and dropping it into the Output Folder window (figure 7.10). Once all variables are selected, create an output product (i.e., graph or file) by clicking on the *Create Graph* (*File*) button.

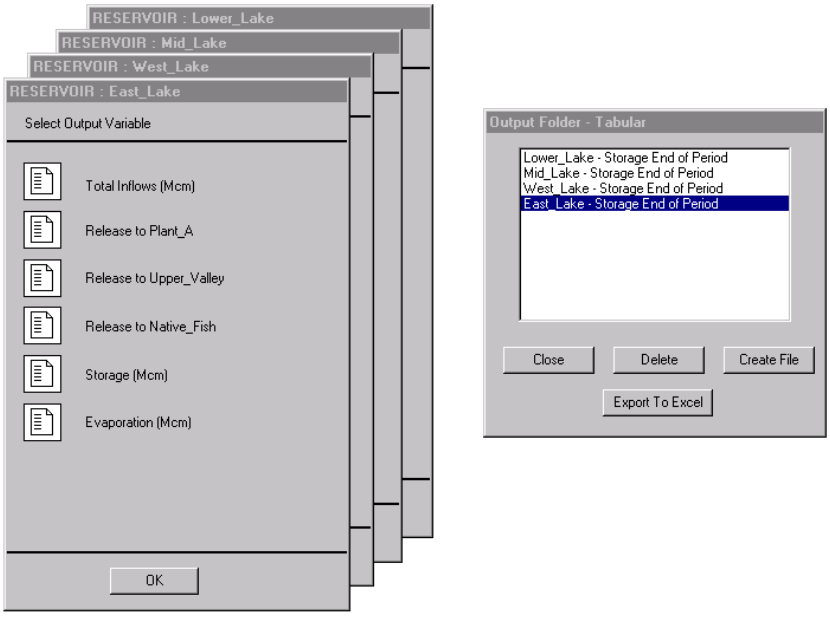


Figure 7.10 Specifying a list of variables for the tabular output folder.

In contrast to single-variable graph windows where information is updated during the sequential optimization process, graphs and tables created by the output folder reflect the state of the system at the moment the output is created (i.e., a static view). If only the optimal state of the network is of interest, the output folder should be created after the water allocation finishes. Printouts of any of the windows, including the NWS, can be obtained by making the window of interest the active window and selecting Print from the File Menu. The Print command also provides most of the customary Windows print settings.

Chapter 8

Model Applications

This chapter presents two hypothetical river systems modeled at a monthly time step. The first, of average complexity, is used to demonstrate various features of Aquarius, including the study of alternative price functions for offstream and hydroelectric demands, and of the effect of improving efficiency of irrigation water use. The second, of minimal complexity, is used to illustrate the concept of economic efficiency that drives the water allocation.

Description of the River Basin System

The first hypothetical river basin is represented by the flow network in figure 8.1, in which the water flows from left to right. The basin comprises three water source subbasins, East Fork, West Fork, and Lower Fork. Two of the subbasins are headwater catchments, at high elevations (left portion of the graph). The third catchment area (Lower Fork) delivers unregulated inflows to the downstream portion of the main water course. Inflows for a real case would typically be based on flow data from the study site. Flows for this hypothetical river basin were taken from rivers of the western United States. The long-term mean-annual discharges of the three catchments are 9,600 Mcm (East Fork), 6,700 Mcm (West Fork), and 6,500 Mcm (Lower Fork). The flow regime is characterized by highly peaked hydrographs, typical of mountainous regions where runoff is dominated by snowmelt. Flows are relatively low during the winter and very high during the spring and early summer months (i.e., April through July).

The natural flows in are regulated by four reservoirs: East Lake, West Lake, Mid Lake, and Lower Lake (figure 8.1). Table 8.1 lists the operational characteristics of the reservoirs. The upper reservoirs (East and West Lakes) have relatively limited capacity to regulate inflows, with active storage/inflow ratios of about 0.3. The third reservoir, Mid Lake, which impounds water from the two upstream river forks, has a storage capacity equal to 70% of the mean-annual discharge at that site. The most downstream reservoir also has limited capacity (storage to natural inflow ratio equal to 0.26), but around 2/3 of its inflows are pre-regulated. When considering the whole basin, the ratio of active storage to natural flows is approximately 1.0.

Table 8.1 Operational characteristics of four hypothetical reservoirs.

Reservoir	------- Storage [Mcm] -------			Sto./Inf.	Elev. vs. Stor.		Area vs. Stor.		Constraints		
	Min.	Max.	Init=Fin.	Ratio	c_1	d_1	c_2	d_2	Min.	Max.	Final
East	2,000.	5,000.	3,500.	0.31	1.86	0.44	1.28	0.59	y	y	y
West	2,000.	4,000.	3,000.	0.30	2.77	0.48	0.26	0.75	y	y	y
Mid	6,000.	17,500.	14,000.	0.70	3.03	0.38	0.30	0.73	y	y	y
Lower	14,000.	20,000.	17,500.	0.26	0.79	0.44	1.00	0.68	y	y	y

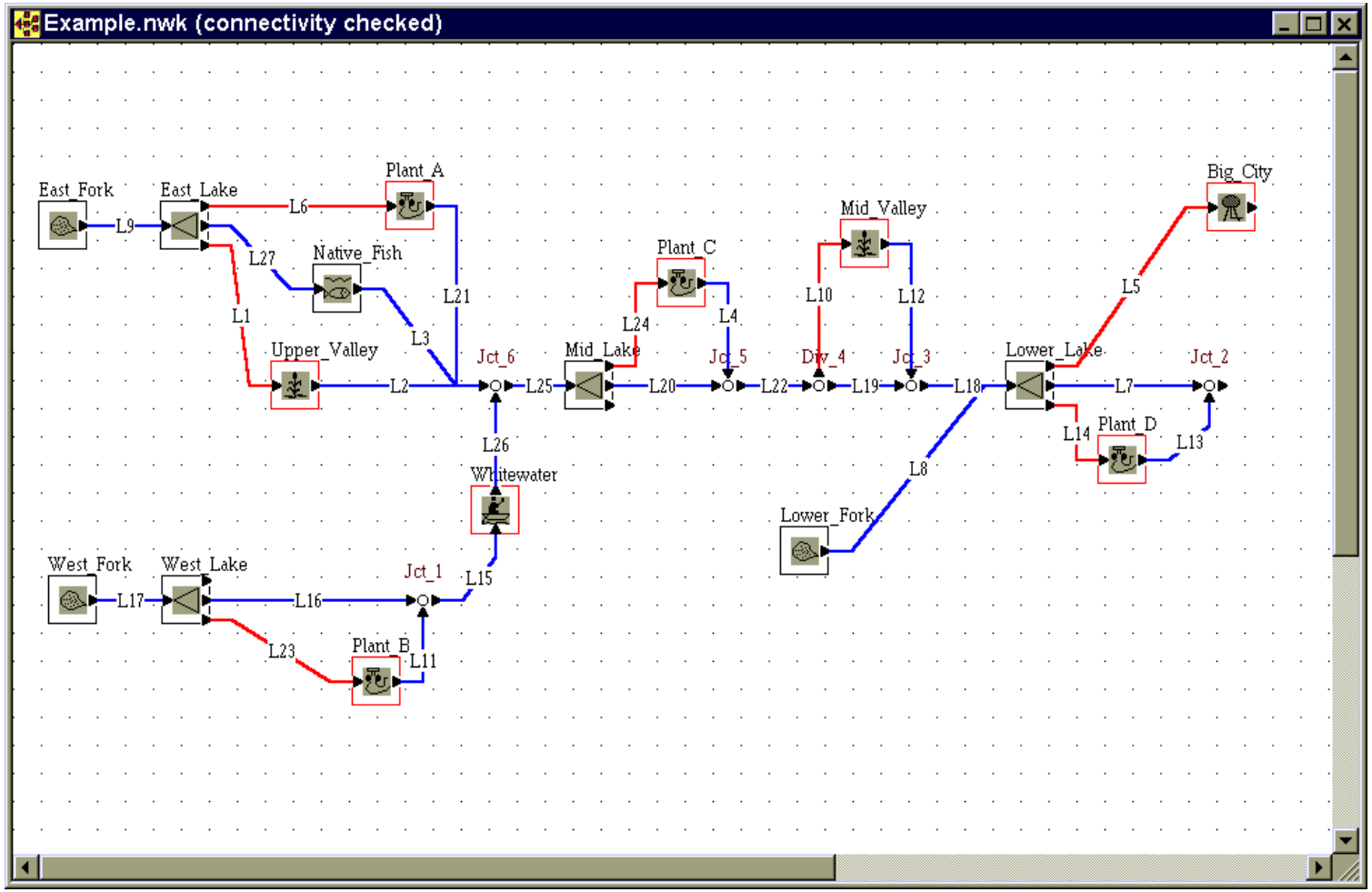


Figure 8.1 Flow network of an hypothetical river basin system.

Thus, the system contains enough active storage to accommodate the total amount of water generated by the three catchments during an average hydrologic year.

Table 8.1 also provides information about the elevation-storage and area-storage relations for the four reservoirs (equations (3.4a) and (3.4b)). Monthly evaporation rates (which would typically, in a real case, be estimated from data gathered at nearby meteorological stations) were set equal to 30, 35, 40, 50, 65, 70, 85, 70, 60, 50, 40, and 35 mm/month, from January through December, respectively for all reservoirs. Data pertinent to the spillways are set to zero (not used for operation at monthly time intervals). The three operational constraints for reservoirs, minimum, maximum, and final storage, are enforced according to table 8.1.

Hydropower is generated using releases from the four reservoirs. Due to existing topographical conditions, the two high elevation reservoirs, East Lake and West Lake, are connected to run-of-river powerplants, A and B, by canals that run parallel to the river at an almost constant elevation. It is reasonable to assume that the two power facilities operate under fixed-head conditions (see figure 3.4, right side). The remaining two powerplants, C and D, are located in the intermediate and lower portions of the system, operate directly connected to the reservoir, and are subject to variable hydraulic heads (see figure 3.4, left side). Table 8.2 describes the power facilities.

Table 8.2 Characteristics of four hypothetical hydropower facilities.

Utility	Installed Capacity [Mw]	Design Discharge [m3/s]	Group Efficiency [-]	Scheduled Maint.	-- Energy Rate -- a_1 [Mwh/Mcm]	b_1	Plant Release Min. [Mcm]	Max.	Constraints Min.	Max.
Plant A	350	920	0.90	no	97.15	0.00	100	≈2,400.	yes	yes
Plant B	300	600	0.90	no	164.13	0.00	100	≈1,600.	yes	yes
Plant C	450	800	0.90	no	163.76	0.04	100	≈2,100.	yes	yes
Plant D	250	1,600	0.90	no	89.66	0.02	250	≈4,200.	yes	yes

We assume uninterrupted service for maintenance or repairs of the generation groups (all monthly coefficients are equal to one). Moreover, minimum powerplant releases (discharge per month) are entered as indicated in table 8.2. Maximum releases are automatically computed by the model from the specified powerplant design discharge and maintenance schedule coefficient (by clicking the Reset button in the Maximum Releases dialog box). Maximum and minimum powerplant releases are enforced in the formulation of the problem by enabling the corresponding constraints in the Operational Constraint box.

Two separate outlet works in East Lake Dam control releases from the reservoir, one on each bank. The left-bank reservoir outlet conveys water into the run-of-river hydroelectric Plant A. Characteristics of the powerplant are in table 8.2. The right-bank outlet discharges into a canal that conveys water to the Upper Valley agricultural area. Fifty percent of the irrigation withdrawals are assumed to return to the natural channel via ground water accretion, far downstream from the dam. Minimum and maximum water

allocations for the Upper Valley zone are listed in table 8.3. However, all the operational constraints for the Upper Valley demand area (minimum, maximum, seasonal and firm water) are disabled for this exercise.

Table 8.3 Offstream and instream demand areas for the hypothetical system.

Demand Area	Monthly Demand Min. [Mcm]	Monthly Demand Max. [Mcm]	Return Flow Coefficient [-]	------ Constraints ------ Min.	Max.	Seas.	Firm
Upper Valley	0	1,000.	0.5	no	no	no	no
Mid Valley	0	2,000.	0.3	no	no	yes	no
Big City	0	1,000.	0.0	no	no	yes	yes
Native Fish	var.	4,000.		yes	no	no	no
Whitewater	var.	4,000.		no	no	no	no

The central link extending downstream from East Lake reservoir (figure 8.1, link 27), represents the natural riverbed. This portion of the river is assumed to have native fish species whose populations have declined since reservoir construction, thus becoming an environmentally sensitive area. Flow requirements were determined using a flow-habitat model as part of a fish recovery program. The recommended mean-monthly flows for the fish habitat protection area (figure 8.1, Native Fish) are 40, 40, 40, 60, 80, 120, 140, 100, 60, 40, 40, and 40 Mcm for the months of January through December, respectively. The recommended minimum releases are aimed at reestablishing some of the natural variability of the flow regime.

The West Lake reservoir regulates natural flows contributed by the West Fork subbasin. The reservoir supplies water for the run-of-river Powerplant B, located on the right-bank of the river. Characteristics of the plant are in table 8.2. The river reach downstream from West Lake but upstream of the junction with the East Fork (Jct 6) is used extensively for recreational purposes, mostly rafting and kayaking. This water use is represented in the flow network by the instream Whitewater user (figure 8.1). Operation of the commercial recreational activities is from May through September.

Regulated flows from the East and West Fork Rivers enter Mid Lake reservoir, where they are regulated again. Releases from Mid Lake Dam are used to generate power at Plant C, which is a variable-head powerplant. Characteristics of Plant C are in table 8.2. Turbine flows are returned to the river at the toe of the dam. Further downstream, water is diverted to an irrigation demand zone named the Mid Valley agricultural area. Thirty percent of the diverted water returns to the stream (table 8.3), which implies a 70% consumptive use. Maximum and minimum diversion channel capacity are indicated in table 8.3, though they are not enforced in the example. However, whatever annual volume of water the model delivers to this region must match the seasonal demand of the crops grown there, which is distributed among months January through December as follows: 0.0, 0.0, 0.0, 0.05, 0.10, 0.15, 0.25, 0.25, 0.15, 0.05, 0.0, 0.0.

Controlled releases from Mid Lake (minus Mid Valley consumptive use) and inflows from the Lower Fork tributary enter Lower Lake. There are two controlled releases from Lower Lake Dam: into Plant D, which is a variable-head powerplant (table 8.2), and into a canal that conveys water to a municipal and industrial demand area named Big City. Big City is a transbasin diversion from which no return flows are possible, as evidenced by the lack of a return link. Big City has a firm contract for 7,000 Mcm per year, which implies that at least that amount of water should be delivered every year. Moreover, the water to be delivered must match the following seasonal distribution (from January through December): 0.07, 0.07, 0.075, 0.08, 0.09, 0.10, 0.10, 0.10, 0.09, 0.08, 0.075 0.07.

Figure 8.1 shows the names of the system components as entered by the user, and the numbers assigned automatically by the model to links and nodes (shown only for junctions and diversions). The model may randomly change the numbering of links and nodes every time the connectivity of the network is checked. A change in the numbering of nodes and links implies a possible change in the mathematical arrangement of the system components when the optimization problem is formulated (Chapter 6, Mathematical Connectivity of System Components). Slightly different optimal solutions should be expected from different mathematical network arrangements due to limitations of numerical precision. Also, as mentioned in Chapter 7, changes in the prescribed maximum number of iterations per QP sequence and the value of the accuracy parameters may also cause slight changes in the final optimal solution.

Once network connectivity is updated (indicated by *...connectivity checked*) at the top of figure 8.1), eight links turn from blue to red. Red links indicate the location in the network where decision variables are created by the model to solve the water allocation problem. Similarly, red lines framing eight water users indicate that they economically compete for water.

Defining Demand Functions

The demand functions used in this example reflect the general structure of prices in Chapter 4, Benefit Functions. Monthly prices for energy are assumed equal for all months and for all power facilities. This is a reasonable assumption considering that all powerplants sell their energy to the same electrical grid system. Furthermore, downward slopping demand curves, equation (4.3), reflect the difference in energy prices from on-peak to off-peak hours; the rate of decay is constant for all months. Table 8.4 has information on hydropower economics.

The only instream user economically competing for water is the water-based recreation area Whitewater. This highly seasonal activity, running from May through September, is represented by linear demand functions, equation (4.25). The seasonality can be inferred from the values of the coefficients of the price functions in table 8.5, which shows values different from zero only for May through September.

Price functions are seasonal for the Upper Valley irrigation area (growing seasons from April through October) and seasonalness for Mid Valley. The coefficients of the exponential decreasing price functions, equation (4.15), are shown in table 8.5. Prices are equal to zero for the nonirrigation months. For the transbasin urban demand zone, Big City, prices also decay exponentially with quantity supplied, equation (4.20), although, in contrast to the agricultural zone, municipalities and industries consume water all year around. This is indicated in table 8.5 by the nonzero values of demand function coefficients for all months of the year.

Table 8.4 Information on hydropower economics.

Hydroplant	Avg. Energy Price P [$/MWh]	P_s	Price Function a_2 [$/MWh]	b_2
Plant A	30.	30.	46.75	1,712.
Plant B	30.	30.	46.75	2,085.
Plant C	30.	30.	46.75	2,917.
Plant D		30.	30.	46.75
		800.		

Table 8.5 Economic information on instream and offstream demand areas.

Month	Whitewater a_5 [$/Mcm]	b_5	Upper Valley a_3 [$/ Mcm]	b_3	Mid Valley a_3 [$/Mcm]	b_3	Big City a_4 [$/Mcm]	b_4
Jan	0.	0.	0.	0.	0.	0.	38,700.	78.
Feb	0.	0.	0.	0.	0.	0.	49,800.	92.
Mar	0.	0.	0.	0.	0.	0.	65,200.	118.
Apr	0.	0.	40,000.	662.	16,000.	485.	71,200.	134.
May	2000.	2.0	40,000.	749.	16,000.	485.	76,000.	145.
Jun	2000.	2.0	40,000.	814.	16,000.	485.	79,600.	155.
Jul	2000.	2.0	40,000.	857.	16,000.	485.	85,000.	164.
Aug	2000.	2.0	40,000.	890.	16,000.	485.	83,100.	160.
Sep	2000.	2.0	40,000.	749.	16,000.	485.	73,400.	141.
Oct	0.	0.	40,000.	543.	16,000.	485.	67,800.	115.
Nov	0.	0.	0.	0.	0.	0.	56,700	88.
Dec	0.	0.	0.	0.	0.	0.	41,500.	71.

Note: parameters b cannot assumed the value zero, hence enter a small number (e.g., b=1)

Finding an Efficient Water Allocation

This section describes the water allocation for the hypothetical river basin in figure 8.1 given the water prices and operational constraints described earlier. The problem was solved over a two-year period using monthly time intervals. The optimization horizon was also set equal to 24 months, making the quasi-continuous optimization procedure unnecessary. Because only a small number of operational constraints was specified for the network, the model finds a water allocation based mostly on the water value. After this baseline case is solved, conditions are modified for different portions of the network to illustrate specific model capabilities.

Initial Feasible Solution

The flow cascading algorithm (Chapter 5) provides the initial feasible solution (IFS) for this problem. The approach consists of simply cascading flows through the reservoirs, avoiding storage regulation when possible, and assigning water to instream and offstream users provided that reservoirs' and water users' operational constraints are not violated. The analyst can force the model to stop immediately after finding an IFS by entering “0” (zero) *Number of Sequences* in the corresponding dialog box (see figure 7.7). Figure 8.2 displays some selected graphical outputs, created by the model, that illustrate the state of the river-reservoir system after the IFS was found.

The storage trajectories for the reservoirs indicate constant reservoir levels for two of the four reservoirs. Figure 8.2 shows monthly releases from East Lake Dam to Plant A, Rare Fish and Upper Valley. The IFS algorithm satisfies minimum required flows at the Native Fish river reach and then arbitrarily chooses any competing water user (Plant A in this example) to which to allocate the remaining flows. For months in which the powerplant capacity was exceeded (months 5, 6, and 16), the extra reservoir inflows were directed toward the Upper Valley irrigation area. Reservoir evaporation is also satisfied. Release conditions from Mid Lake are different from those at East Lake in that a single user (Plant C) is directly linked to the reservoir. Because the maximum capacity of the powerplant is at times exceeded, the reservoir is forced to regulate its inflows to avoid spillages.

When encountering offstream demand areas that claim water directly from the natural channel, rather than from a storage reservoir as Upper Valley does, and when no minimum flows are enforced, the IFS algorithm maintains water in the river rather than diverting it. Figure 8.2 shows no water allocated to Mid Valley agricultural zone. Note that zero flows is a feasible solution when seasonality is required.

The value of the total benefits from this arbitrary pattern of water allocation over two years of operation was calculated by the model as $1,103.529 million. Although this initial solution is feasible, it is far from being an efficient allocation of water, as demonstrated next. The set of parameters chosen to control the optimization sequential process and the accuracy of the computations for this example network coincide with those shown in figure 7.7. The water allocation problem is solved using the “implicit” approach for modeling reservoir evaporation.

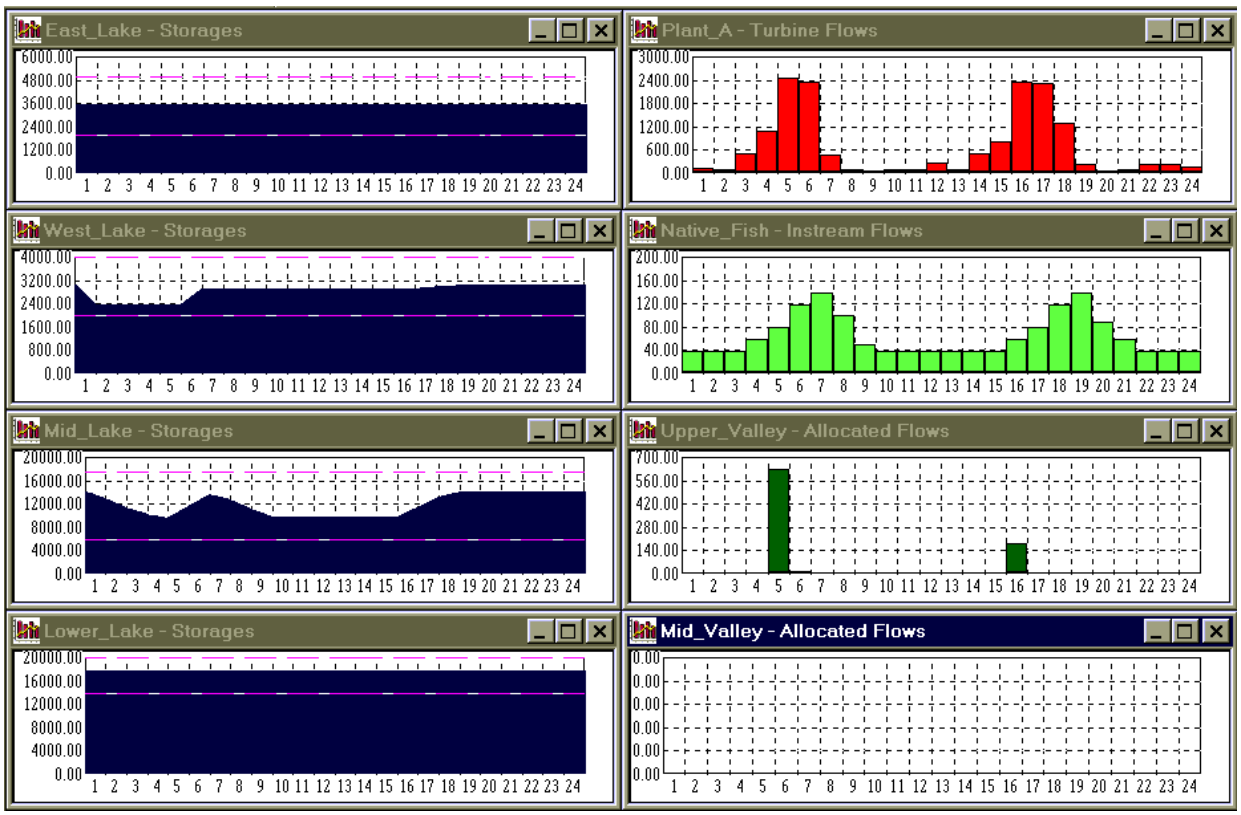


Figure 8.2 Selected graphical outputs from the initial feasible solution.

Final Solution

A crucial element during the allocation process is the monotonic decrease in the marginal price of allocated water with the increasing availability of flows. Reservoirs are also important components during the allocation of water in the basin because flow regulation allows for releases that efficiently satisfy instream and offstream demands. Figure 8.3 shows the high contrast between the uncontrolled inflows and the controlled outflows from the West Lake reservoir.

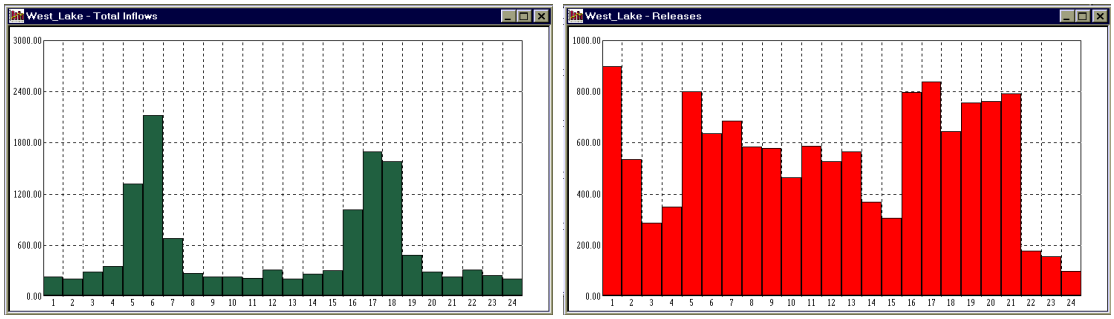


Figure 8.3 Uncontrolled inflows and controlled outflows from West Lake.

Figure 8.4 shows selected graphs of the result of the optimization. The two headwater reservoirs absorb most of the variability of the natural inflows, creating favorable conditions for the rest of the basin to generate hydropower and distribute water during the seasons in which it is needed. Water levels in East and West Lake reservoirs oscillate from empty to full to avoid spilling the large volumes of inflow associated with snowmelt. Because Plants A and B are run-of-river plants (i.e., their energy generation is not a function of reservoir storage levels), they impose no limitations in the oscillation of the water levels in the two headwater reservoirs. Contrarily, at Mid Lake Dam, with a variable-head powerplant, almost constant and maximum water levels are maintained during the whole optimization horizon to maximize hydropower production. High reservoir levels are also maintained at Lower Lake, which besides receiving the regulated inflows from the upstream portion of the basin, also captures uncontrolled inflows from Lower Fork Basin, forcing an appreciable degree of regulation at the reservoir.

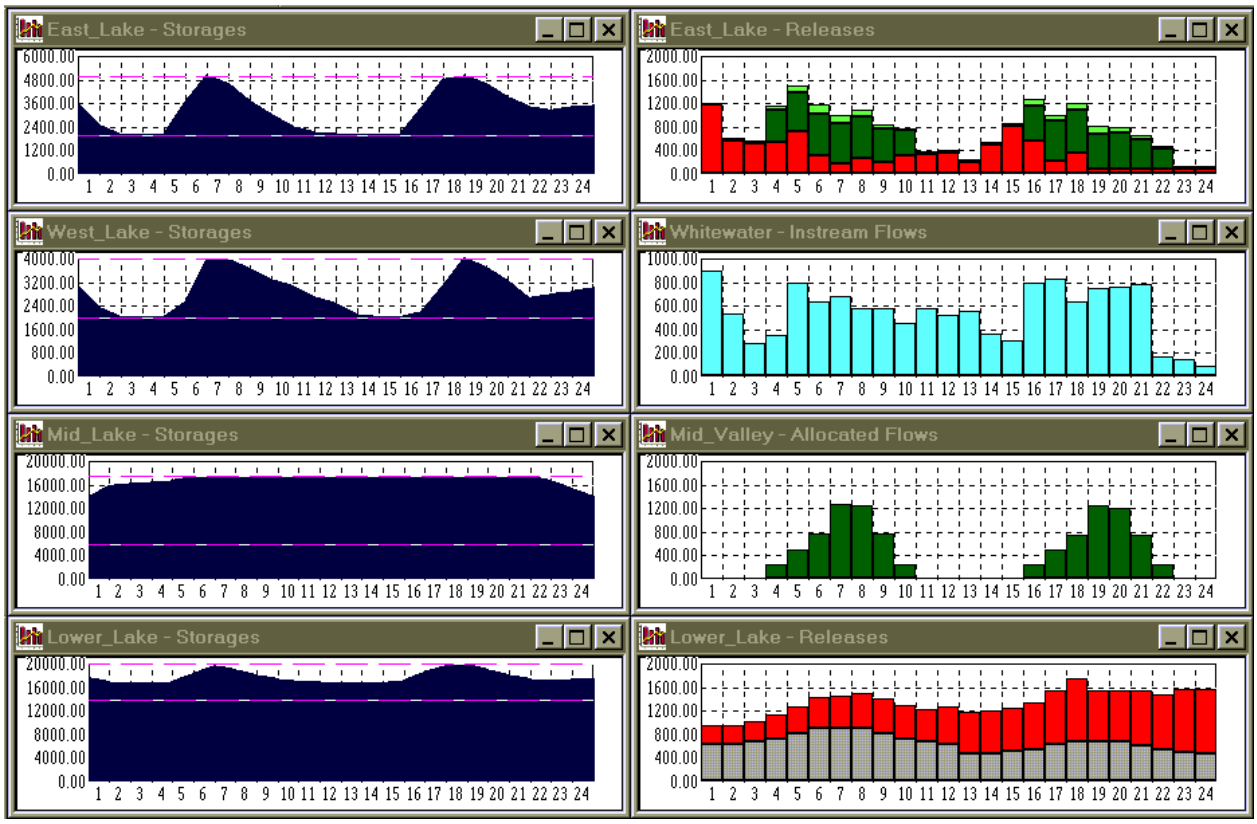


Figure 8.4 Selected graphical outputs from the final optimization solution.

Releases from East Lake are shown in figure 8.4 (upper-right graph, stacked bars). Water diversions into the Upper Valley irrigation area (middle bars) display the classical seasonality of irrigation demand, in this case controlled exclusively by the monthly price functions, since no seasonality constraint was enforced for Upper Valley. Water is diverted during the growing season, with zero flows during months outside the irrigation season (zero economic benefits for those months, see table 8.5). Optimal releases for Plant A satisfy on-peak energy demand throughout the entire optimization horizon, assigning extra releases (to generate lower value energy) only during the first few months of every year. Link 27, the river reach where the fish protection area was established, received no more flows than the ones enforced by the user via the minimum flow constraint. This is expected since the optimization algorithm gives preference for releases to users generating revenue, and Native Fish has no economic benefits attached to it.

Releases from West Lake, after passing through Plant B, become instream flows in the West Fork River where the Whitewater recreation area is located. As indicated in figure 8.4, the model releases relatively larger flows from West Dam during periods 5 through 8 and 17 through 20, the months of economically valuable rafting and kayaking use.

Optimal diversion for irrigation at Mid Valley also display the classical seasonal pattern, but this time they are due to the enforcement of the seasonal pattern constraint (the price functions are all equal). The volumes of water allocated each irrigation season are very similar but not identical, with 30 percent of the diverted flow returning to the stream during the same month in which is diverted (r=0.3).

Optimal releases from Lower Lake are displayed by the stacked bar diagram in the lower right-graph of figure 8.4. The lower bars correspond to water supplied to the Big City M&I demand area; the upper bars represent water released for hydropower to Plant D. Optimal flows allocated to Big City follow the seasonal pattern indicated on page 137. Releases to Plant D tend to follow the storage fluctuations in the reservoir, being small as the reservoir builds up storage and largest during those months with the highest water levels at the reservoir.

Evaporation losses represent, on average, a relatively small amount of water when compared to the total inflows to the reservoirs, 2.3% for headwater reservoirs and 3.8% for Lower Lake, but with important monthly variations. Evaporation losses do not influence the storage patterns significantly, thus justifying using the implicit model for reservoir evaporation. Moreover, reservoir spills do not occur for the period of record analyzed in this exercise.

As illustrated in figure 5.1, the optimization algorithm SQP searches for the optimal allocation of water by successively solving quadratic programming problems. Figure 8.5 shows the evolution of the value of the global objective function as it progresses toward the optimal solution for this example. There is a substantial improvement in the water allocation during the first few sequences, accompanied by a drastic increase in revenues, followed by a relatively flat portion of the revenue curve where only small changes occur during the remaining sequences. The search

for the optimum stops when: a) the maximum number of sequences is reached (40 in this example); b) the change of global return between two consecutive QP sequences becomes less than $1000 (see figure 7.7); or c) the solution runs into some infeasibilities (detected by the third accuracy parameter in figure 7.7). In this example network, the second termination criterion stopped the calculations at sequence 29. At this point, revenues for the two-year period computed by the model totaled $1,649.414 million.

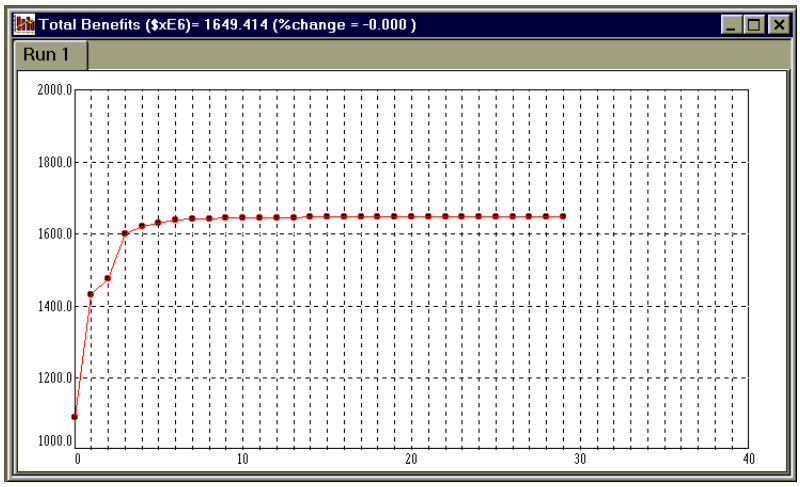
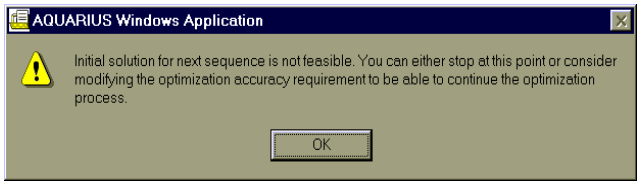


Figure 8.5 Evolution of the global objective function.

If the third criterion stops the optimization, a warning message alerts the user to either keep the solution obtained that far, or consider increasing the constraint infeasibility accuracy parameter and resume the optimization process. This situation may happen only when the implicit approach for modeling reservoir evaporation is adopted.



Changes in Offstream Water Demand

We now introduce a change in the demand of water from an offstream zone to demonstrate how the new problem can be solved with minimum computational effort, and discuss the implications of the change. The allocation of water to the Upper Valley irrigation area for the baseline case relied exclusively on the demand curves specified for each time period. Note that the optimal allocation displays a seasonal variability consistent with the monthly demand functions in table 8.5 (see figure 8.4). We now assume that flows are also required for the nonirrigation month January at Upper Valley. The new use will be incorporated into the model by altering the economic conditions in the network rather than by imposing a minimum flow level constraint. For the baseline case the demand function had null parameters for January (table 8.5); now they are set equal to those for July (a_3=40,000 and b_3=857). The user can solve the new water allocation problem by altering the marginal price of water at Upper Valley for January, validating the network connectivity, and solving the optimization problem to find the efficient water allocation policies under the new economic condition.

However, because changes in the price structure do not invalidate feasibility in the network, the user can proceed from the last optimal solution, in this case the baseline solution, to the new optimal condition. Changes in marginal prices can be introduced any time during the execution of the optimization or at the end of the sequences. If the change is introduced as the application is executing, the graphical outputs will indicate how the model immediately starts redirecting the allocation of water to accommodate the new economic conditions. If the change is introduced after AQUARIUS has reached an optimum, the model will adopt the last optimal solution as the IFS for the new round of optimization. For a minor change in price, the model will find the new optimum very quickly. Figure 8.6 shows the results of the above outlined procedure. The water allocation at Upper Valley shows positive flows for January (note that months 1, 2, 3, 11 and 12 have zero flow allocation in the baseline solution, figure 8.4). The allocation of flows to Upper Valley during January reflects the willingness of the irrigation area to compensate other users for the extra water demanded for that month. In other words, a new potential Pareto optimal arrangement was found.

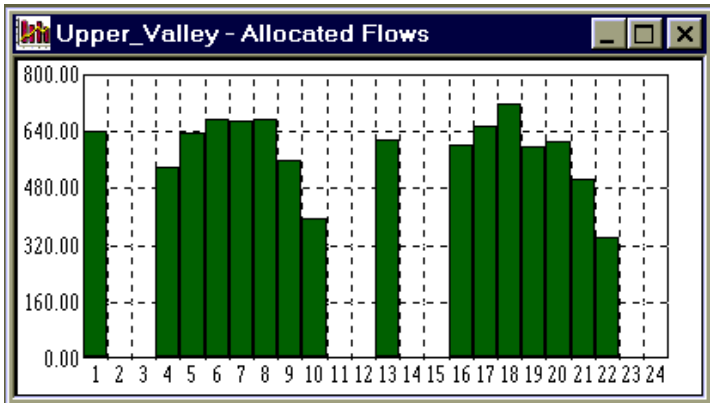


Figure 8.6 Change in offstream water demand.

As an additional example of a change in offstream water demand, consider an improvement in irrigation efficiency, a change that can be characterized in terms of physical rather than economic factors. Either by structural measures or conservation practices, the water duty for irrigation often can be decreased. Although this may imply several modifications to the original baseline case, we will simply increase the amount of return flow that originates from the Upper Valley irrigation area from 0.5 to 0.7. This has practically the same effect on the network of reducing the water duty, since more water will be left in the river for use by other system components downstream.

After solving the network with the new Upper Valley return flow (note that when a physical variable is changed a completely new run is required), the benefit from the network operation increases from $1,649.414 million to $1,700.151 million, a $50.7 million (3.1%) change over the two-year period. Additional information can be extracted to identify the downstream water uses who benefit from this improved economic condition. The increase in benefit provides economic incentive for negotiations among the multiple users in the basin to finance the structural improvements necessary to conserve water in the basin.

Change in Energy Price

Although unit revenues for hydroenergy are variable according to the type of energy being generated, on-peak vs. off-peak (figure 4.2), some power systems are compensated economically for the energy generated using a single rate, regardless of the time of the day in which the energy is delivered. The purpose of this exercise is to demonstrate how this case can be modeled by AQUARIUS and to show the operational consequences of such an assumption.

Within the AQUARIUS formulation, adopting a constant unit price for energy is equivalent to replacing the exponential curve in equation (4.3) by the single step function (i.e., a constant value for all plant utilization factors) in equation (4.31). Then, the value assigned to the parameter a_2 will represent the constant rate paid for hydroenergy. A constant price specified by a_2=15 $/Mwh was adopted for one of the powerplants, Plant D, while maintaining the rest of the hypothetical system at levels of the baseline case described above. The system operation was reoptimized under these new conditions. The values of the old and new powerplant releases from Plant D are shown in figure 8.7.

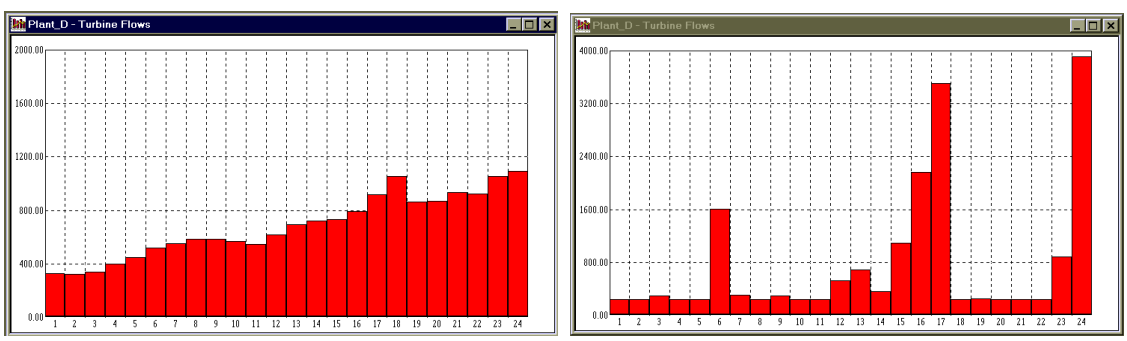


Figure 8.7 Hydropower releases with decreasing and constant energy price.

The model for the exponential price function (left graph) shows power releases covering the on-peak volumes for all time steps (since on-peak releases have a higher price) plus releases during off-peak periods. When interpreting the series of releases from Plant D, remember that the upper portion of the basin is holding most of its inflows during the first months to build up storage in the reservoirs. In contrast, when the energy price function for Plant D is a constant (figure 8.7, right graph), the powerplant is not compelled to satisfy on-peak releases as before. Although power releases occur in a more random pattern, they contribute more to total system revenue, which depends as well on other reservoir functions that encourage gains in storage whenever possible to maximize the amount of energy generated with the same amount of water and to satisfy the demand from Big City). Of course, this series of power releases would be unacceptable in a real system where, typically, minimum power releases would be imposed to ensure that a minimum amount of energy is generated each month (imposing such minimums is also a viable option using AQUARIUS).

Economic Efficiency for a Simple Case

In this exercise, we use a simple flow network to illustrate the basic concept of economic efficiency used in the model to drive the allocation of water in a river basin. This network consists of a single reservoir with two offstream demand areas, The Farm and The City, which withdraw water directly from the reservoir (figure 8.8, upper-left). The irrigation and urban zones have completely different demands regarding the amount and seasonal distribution of water required. The Farm receives water only during the growing season, April through October, whereas The City receives water all year. Monthly price curves were provided for the two water uses according to their seasonal demands. Furthermore, no minimum or maximum limits on releases are enforced. The only constraints are upper and lower bounds on reservoir storage, set equal to 5,000 and 2,000 Mcm, respectively, as indicated by the dashed lines in the upper right graph of figure 8.8.

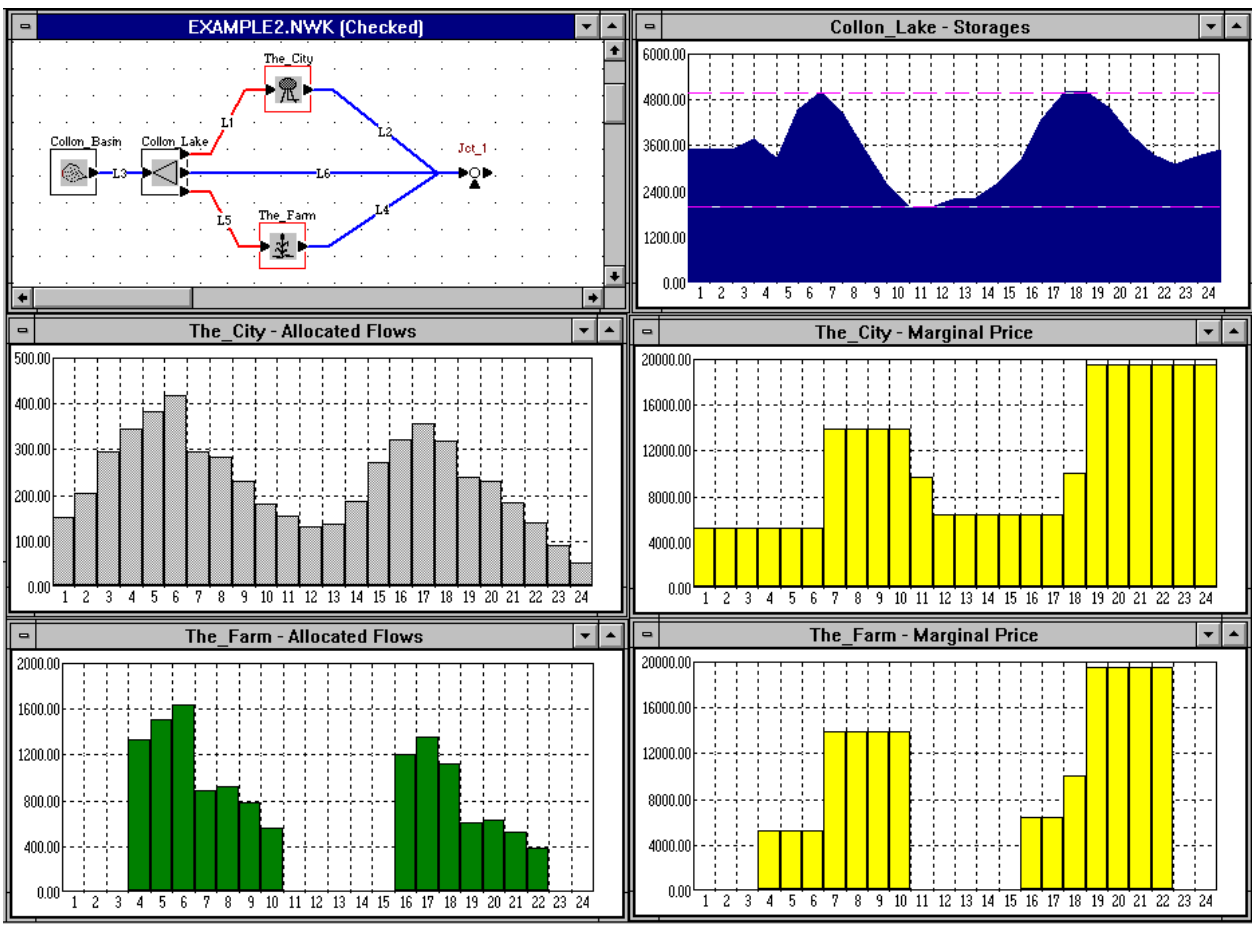


Figure 8.8 Conditions of economic efficiency in water allocation.

Figure 8.8 shows the most significant outputs from the optimal solution: the reservoir storage trajectory, the optimal releases, and the marginal prices of water for the two uses computed at the point of optimality. As stated in Chapter 2, the model will allocate releases at a constant marginal price, provided that an unbounded solution to the water allocation problem is obtained.

Figure 8.8 shows that the model reached the optimum when marginal prices were equalized for the two demands (compare the two marginal price bar graphs). Once the optimal solution has been reached, the value of water for each user, at the margin, is the same. This is not to say that the optimally allocated flows are equal for the two users. In fact, one can observe that the two users receive very different amounts of releases.

Under optimal conditions, the model keeps the marginal prices constant in time provided that the solution of the problem is unbounded. Figure 8.8 shows that once the storage in the reservoir reaches the upper or lower bound, the solution becomes bounded (i.e., it is no longer an interior solution) and the marginal price changes. The solution of the reservoir problem is interior from time period 1 through 6; thus, the marginal prices remain constant during those 6 months. Similar behavior can be observed for other periods with interior solutions (e.g., 7-10, 12-17, 19-24). This demonstrates, as discussed in Chapter 2, that the marginal benefit of the release remains constant in time if the allocation is optimal.

Software Performance

The time of execution of an application depends on many factors. Among them are: the size of the flow network (the number of decision sets); the topology of the network (the type of water uses and how they interconnect); the number and type of operational constraints (whether the problem is mostly constrained or unconstrained); the formulation selected for calculating reservoir evaporation (implicit or explicit); the length of the period of study (including the period of analysis, the optimization horizon and the overlapping period); the value of the parameters controlling the QP sequential process (maximum number of QP sequences allowed and number of iterations per sequence); the value of the parameters controlling accuracy (for general calculations and for checking the feasibility of the solution); and the value of the parameters controlling when to stop the optimization (minimum allowed change between consecutive values of the objective function).

Definitively, the size of the flow network and the length of the period of analysis are the two main factors determining the execution time. For a given network, the execution time increases exponentially with the optimization horizon. For instance, the Example network is solved in 8 seconds for a 12 month optimization horizon, 57 seconds for 24 months, and 183 seconds for 36 months. The model was run in a personal computer with a 500 MHz Intel Pentium III processor (the execution times do not include graphical output display between sequences).

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