

AQUARIUS: AN OBJECT-ORIENTED MODEL FOR EFFICIENT ALLOCATION OF WATER IN RIVER BASINS

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ABSTRACT: This paper introduces AQUARIUS, a state-of-the-art computer model devoted to the temporal and spatial allocation of water among competing uses in a river basin. The model is driven by an economic efficiency operational criterion that calls for the reallocation of stream flows until the net marginal returns in all water uses are equal. This is achieved by systematically examining, using a nonlinear optimization technique, the feasibility of reallocating unused or marginally valuable storage and releases in favor of alternative uses. Because water systems can be interpreted as objects of a flow network in which they interact, the model considers each component or structure of a water system as an equivalent node or structure in the programming environment as well, using an object-oriented programming language (C++). This programming structure, combined with modern computer graphics capability, allows interactive use of the model to easily examine *what if...* scenarios.

KEY TERMS: water allocation, economic efficiency, object-oriented programming.

INTRODUCTION

To efficiently manage today's increasingly complex water systems, new modeling tools are needed—tools dedicated not only to the continued support of the traditional uses, but also to the growing societal recognition of nontraditional water uses. Traditional water uses—for which most existing water management systems were designed and are typically operated—include flood control, hydropower, irrigation, and urban water supply. Nontraditional uses include preservation of biological and geomorphological integrity of a river, as well as provision of opportunities for water-based recreation.

This paper introduces AQUARIUS, a state-of-the-art computer model devoted to the *temporal* and *spatial* allocation of flows among competing water uses in a basin. We envision AQUARIUS as an analysis framework rather than a single dedicated model for water allocation. In this first version of the model, Version 96, we adopted an economic criterion for determining water allocation. This was done primarily because economic demands have traditionally played a key role in water allocation decisions, and also in light of the greater accessibility of economic value estimates for some nontraditional water uses. The software runs on a personal computer under a Microsoft Windows 95 or Windows NT operating system. Documentation of the model can be found in Díaz and Brown (in press).

In the classroom, AQUARIUS can be used as a tool for teaching water resources planning and management by helping instructors convey to their students the intricacies of water allocation in river basins with multiple water uses. Because of the ease with which flow networks can be created and altered, and with which graphical and text output can be created and compared, students will be able to explore *what if...* scenarios conducive to a more comprehensive understanding of the interrelationships among water demands and the year-to-year variability of water supplies. Students interested in water resources economics will also benefit from this analysis framework in which the efficiency of water allocation can be made the primary—and the only, if so desired—driving force for water allocation.

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EFFICIENT ALLOCATION OF WATER

AQUARIUS V.96 is driven by an *economic efficiency* operational criterion that calls for the reallocation of stream flows until the marginal returns in all water uses are equal, i.e., until a potential Pareto optimal arrangement is reached. Each traditional use (e.g., hydropower) and nontraditional use (e.g., water-based recreation) is represented by a *demand curve*, also known as a marginal benefit function. An example of a demand curve is shown in Figure 1 for instream recreation along the Bitterroot River in Montana, involving dry fly fishing, floaters and shoreline recreationists.

Because—in contrast to Figure 1—demand curves are more the rule than the exception, AQUARIUS uses exponential models of the form $P = ae^{Q/b}$, with $a > 0$ and $b < 0$, to represent convex (to the origin) demand functions. Under this multipurpose modeling approach, the model systematically examines the feasibility of reallocating unused or marginally valuable storage and releases in favor of alternative or competitive uses, identifying trade-offs between the various water user groups.

For a water use for which the level of allocation has been predetermined but for which the economic demand function is practically impossible to define, the analyst can experiment with surrogate demand curves until the required level of water allocation for that particular use is reached. Indirectly, this approach indicates the societal willingness to pay for incremental increases of flow for the nontraditional water use, or perhaps, the level of economic subsidy required to sustain that use in open competition with other uses in the basin. As will be seen below, the interactive nature of AQUARIUS facilitates such experimentation.

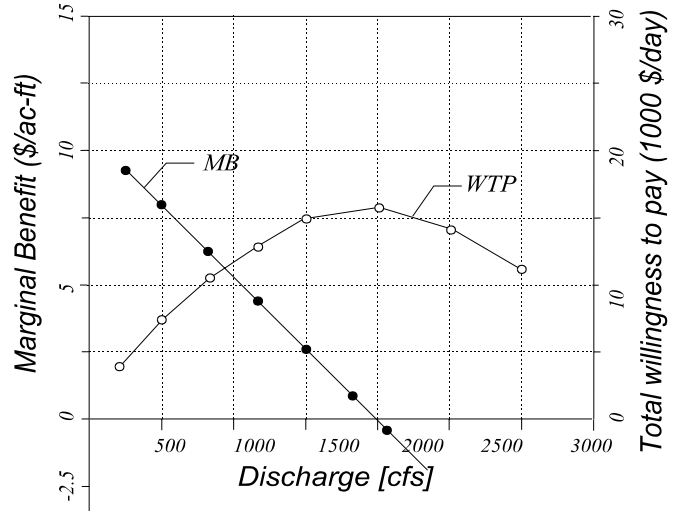


Figure 1. Marginal and Total Recreation Value as a Function of Instream Flow (Duffield et al., 1992).

SOLUTION OF THE WATER ALLOCATION PROBLEM

In the model, water allocation throughout a river system and for an entire planning horizon is based on a global objective which is to *maximize the sum of all economic net benefits* stemming from the instream and offstream uses of water, subject to the operational constraints of the system such as: reservoir storage limits, firm water supply levels, max/min instream flows, max/min diversions, and seasonality of water demands. Given demand functions expressing the net benefits of the various water uses j , the global benefit function (B) to be maximized over the various time periods i is

$$B = \sum_{i=1}^{np} \sum_{j=1}^{nu} \int_0^{a_{ij}} f_{ij}(x_{ij}) dx_{ij}$$

where np is the total number of time periods, nu is the total number of water users, x is the level of output in the demand function $f(x)$, and a denotes the level of allocation. B is maximized when a_{ij} are set such that the marginal prices are equal for all ij (provided that an unconstrained solution to the allocation problem is found). In other words, total benefits are maximized when levels of consumption are such that the marginal benefits for each use across all uses and time periods are equal (note that future net benefits may need to be discounted—a facility not yet included in the model). B can, of course, only be maximized over the j uses for which marginal benefit functions are specified. If relevant uses are omitted because their benefit functions cannot be specified,

the model can still represent them by adding the necessary physical constraints to the formulation.

The water allocation problem postulated above requires consideration of a complex nonlinear objective function. A variety of approaches exist in the literature for solving this type of problem, none of which is uniquely superior or universally proven. The solution technique implemented in AQUARIUS V.96 takes advantage of the special case of the general nonlinear programming problem that occurs when the objective function is reduced to a quadratic form and all the constraints are linear. The method entails approximating the original nonlinear objective function by a quadratic form using Taylor Series expansion and solving the problem as a quadratic programming problem. A succession of these approximations is performed—following a technique known as Sequential Quadratic Programming (SQP)—until the solution of the quadratic problem reaches the optimal solution. This method of solution is an extension of work reported by Díaz and Fontane (1989).

MODELING RIVER BASINS

One of the unique characteristics of AQUARIUS is its implementation using an Object-Oriented Programming (OOP) language (C++). This modeling approach implements the concept of a system as articulated in systems engineering. Water systems are ideal candidates to be modeled under an OOP framework, where each system component (e.g., reservoir, demand area, diversion point, river reach) is conceptualized as an equivalent object in the programming environment (see Diaz and Brown, in press, for details).

Creating a Flow Network

The user interacts with the model through the so-called network-worksheet screen (Figure 2), which allows the analyst to readily represent the water system of interest using the inherent capability of the object-oriented paradigm for graphical representation. The model provides four elements for user interaction: (i) the network worksheet (NWS), (ii) the menus, (iii) the water system components (WSC) palette, and (iv) the object tools palette.

In the NWS each system component corresponds to an object—a graphical node or link—of the flow network. These components are represented by *icons*, based on a pictorial representation of the object. By *dragging and dropping* these icons from the menu, the model creates instances of the objects on the screen. In this manner, one by one, all the necessary system components are created. WSCs can be repositioned anywhere in the NWS or be removed from it. Once nodes (e.g., reservoirs, demand areas) are placed, they can be linked by means of natural river reaches and conveyance structures, which are also objects available from the WSC palette. This operation is carried out by simply left-clicking first on the outgoing terminal of a node, and then on the incoming terminal of the receiving node. This procedure facilitates the assembly or alteration of water systems by simply "wiring up" their system components in the NWS. The creation and alteration of flow networks is further facilitated by copying and inserting an object or whole portions of an existing network onto the same or a new NWS. The *Copy/Paste* procedure not only creates new instances of the object(s), but also duplicates their data structure, creating clones of the original objects.

Entering Input Data

The model's input data have been divided into two basic groups: *physical* and *economic* data. The physical data include the information customarily associated with the dimensions and operational characteristics of the system components, such as maximum capacity of a reservoir, percent of return flow from an offstream demand area, and efficiency of a powerplant. The economic data consist mainly of the demand functions of the various water uses competing for water. The input data entered for any system component remain part of the object, even after the network is saved on a storage disk. When the network is reloaded, all data saved from the previous session are retrieved in exactly the same form.

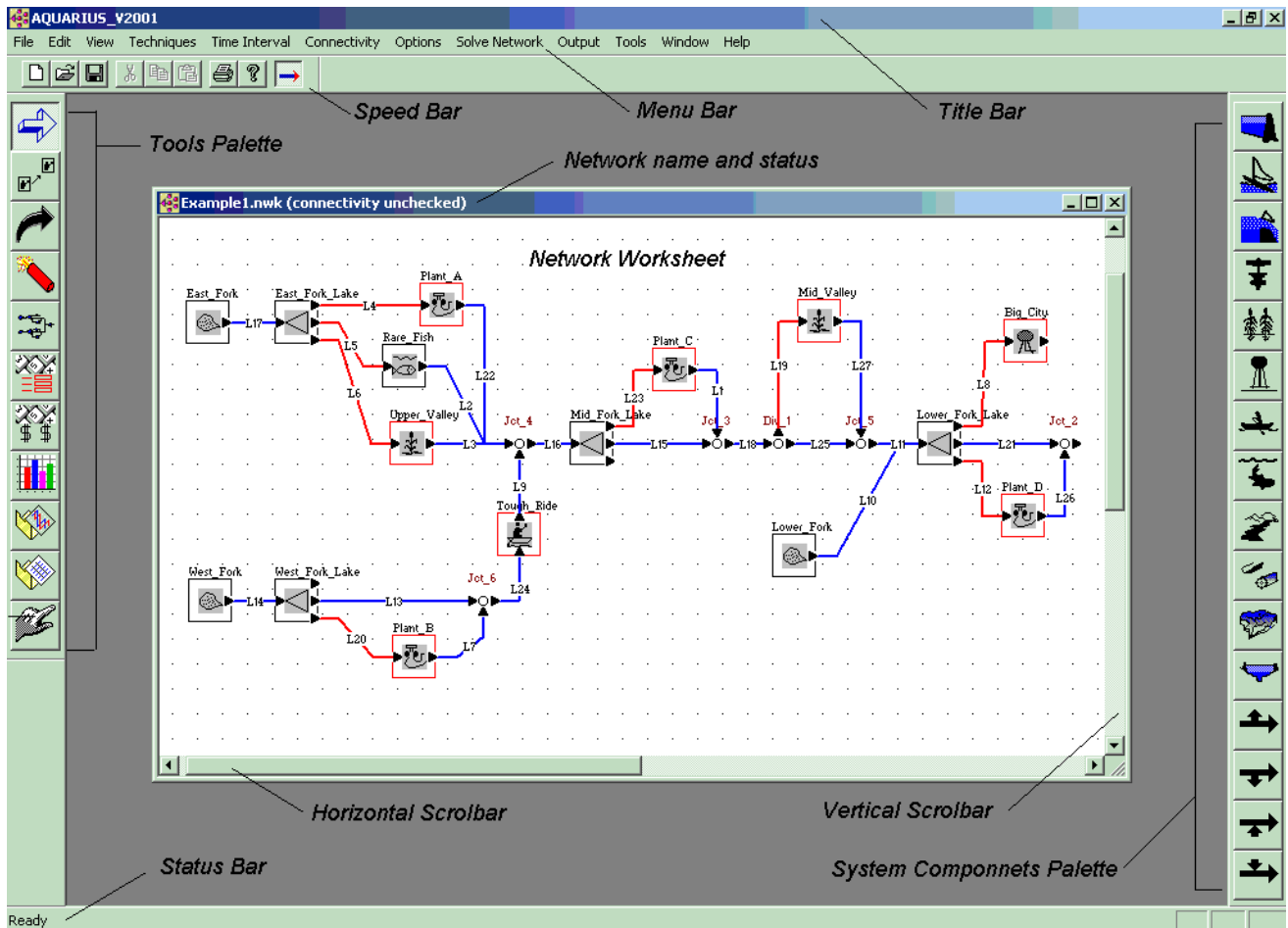


Figure 2. AQUARIUS Network-Worksheet Screen.

Some Operational Aspects

Although the current version implements only a monthly time step, AQUARIUS was conceived to simulate the allocation of water using any time interval of analysis: daily, weekly, monthly, or time intervals of nonuniform lengths. Under the latter scheme, we can, for example, think of a year-long operation horizon subdivided as: the first 7 days (short-term), the following 3 weeks (medium-term) and the remaining 11 months (long-term). This partition of the operation horizon into intervals of different length may coincide with the way inflows to the river system are forecasted. It is envisioned that future versions of the model will support these other time steps.

AQUARIUS can be used in a full deterministic optimization mode (for general planning purposes), or in a quasi-simulation mode, with restricted foresight capabilities. The model distinguishes between the *period of analysis*, used to specify the length of the whole segment of time for which the model will simulate the operation of the system, and the *optimization horizon*, used to specify how far ahead into the future the model should look to build the optimal operational policies. Setting the optimization horizon equal to the period of analysis produces a full-period optimization.

Formulating the water allocation problem entirely within the domain of the objective function provides the user with the capability to redirect the water allocation process in any desirable direction in *real time*, directly from the screen, as the optimization progresses. This unique feature of the model provides the analyst with an expeditious and innovative mode of exploring *what if...* scenarios.

DEMONSTRATION OF MODEL APPLICATION

River flow networks contain a myriad of state, decision and economic variables that the user may need to consider for the analysis. AQUARIUS facilitates the interpretation and analysis of all that information through readily accessible graphical and tabular output display formats. This section demonstrates an application of the model using the hypothetical river basin depicted in Figure 2. The demonstration illustrates a few of the available output displays.

Description of the Hypothetical River Basin

The basin has three water sources: the East Fork, the West Fork, and the Lower Fork subbasins. Two of the subbasins are headwater catchments, located at high elevations (left portion of Figure 2). The third catchment area (Lower Fork) delivers unregulated inflow to the downstream portion of the main water course. The long-term mean-annual discharges for the three catchments are 9,600, 6,700 and 6,500 Mcm (millions of cubic meters), respectively. The flow regime in the region is characterized by highly peaked hydrographs, typical of mountainous regions where runoff is dominated by snow-melt. Flows are relatively low during the winter, and very high during the spring and early summer months, from April through July.

The natural flows in the system are regulated by four reservoirs: East Lake, West Lake, Mid Lake, and Lower Lake (Figure 2). The operational characteristics of the reservoirs, listed in Table 1, are similar to those of actual reservoirs in the western U.S. The upper reservoirs (East and West Lakes) have relatively limited capacity to regulate inflows, with active storage/inflow ratios of about 0.3 (Table 1). The third reservoir, Mid Lake, which impounds water from the two upstream river forks, has a relatively large storage capacity, equal to 70% of the mean annual discharge at that site. The most downstream reservoir is also of limited (medium to low) capacity ($S/I=26\%$), but around 2/3 of its inflows are preregulated. Overall, when considering the whole basin, the ratio of active storage to natural flows is approximately 1.0.

TABLE 1. Information on Storage Capacities.

Reservoir	Storage [Mcm]		Sto./Inf. Init.=Fin. Ratio	Elev. vs. Stor--		Area vs. Stor--		Constraints			
	Min.	Max.		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	yes	yes	yes
West	2,000.	4,000.	3,000.	0.30	2.77	0.48	0.26	0.75	yes	yes	yes
Mid	6,000.	17,500.	14,000.	0.70	3.03	0.38	0.30	0.73	yes	yes	yes
Lower	14,000.	20,000.	17,500.	0.26	0.79	0.44	1.00	0.68	yes	yes	yes

Table 1 also provides information about the elevation-storage and area-storage relations for the four reservoirs. The elevation-storage curve is given by $E = c_1 S^{d_1}$, and the area-storage curve is given by $A = c_2 S^{d_2}$. For simplicity, monthly rates of net evaporation are assumed identical for all reservoirs, and equal to: 30, 35, 40, 50, 65, 70, 85, 70, 60, 50, 40, 35 mm/month, corresponding to the months of January through December, respectively. All data pertinent to the spillways are set equal to zero (not used for operation at monthly time intervals). Furthermore, the three operational constraints for reservoirs, "Minimum, Maximum and Final Storage", are enforced (checked "yes", Table 1).

Hydroelectric energy is generated using releases from the four reservoirs. Plants A and B are run-of-river plants, whereas Plants C and D operate directly connected to their reservoirs, and are subject to variable hydraulic heads. To save space, the details of the four power plants are not discussed here. The plants are included in the network (Figure 2) to give the reader a sense of the full capability of the model.

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 power plant. The right-bank outlet discharges into a canal that

conveys water to the Upper Valley agricultural area. Fifty percent of the irrigation water returns to the natural channel downstream from the dam. Minimum and maximum water allocations for the Upper Valley zone are indicated in Table 2, but the operational constraints for the offstream demand areas ("Minimum, Maximum and Seasonal Demand") remain disabled (checked "no") for this exercise.

TABLE 2. Information on Offstream and Instream Demand Areas.

Demand Area	--- Demand ---		Return Flow Coefficient	--- Constraints ---		
	Min.	Max.		Min.	Max.	Seas.
	[Mcm]					
Upper Valley	0	1000.	0.5	no	no	no
Mid Valley	0	2000.	0.3	no	no	no
Big City	0	1000.	0.0	no	no	no
Rare Fish	var.	4000.		yes	no	no
Tough Ride	var.	4000.		no	no	no

The central link extending downstream from East Lake reservoir represents the natural riverbed. Let us assume that this portion of the river contains native fishes whose populations have declined since the construction of the reservoir, and that a recovery program has been established for the fish, for which flow requirements were determined using a flow-habitat model. The recommended minimum mean monthly flows for the Rare Fish reach below East Lake are equal to: 20, 20, 20, 30, 40, 60, 70, 50, 30, 20, 20, 20 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 that existed before regulation.

West Lake reservoir regulates natural flows contributed by the West Fork River subbasin. The reservoir supplies water for powerplant B, located on the right-bank of the river. The river reach downstream from West Lake, but upstream of the junction with the East Fork, is used for recreational purposes (for the Tough Ride rafting run). The period of operation of the rafting activity runs from May through September.

Regulated flows from the East and West Fork Rivers enter Mid Lake reservoir, where flows are regulated again. Releases from Mid Lake Dam are used to generate power at Plant C. Turbine flows are returned to the river at the toe of the dam, despite the sketch in Figure 2 which may suggest a longer distance before the restitution takes place. Further downstream, in the middle portion of the basin, water is diverted to an irrigation demand zone named the Mid Valley agricultural area. About 30% of the diverted water returns to the stream (70% consumptive use), as specified in Table 2. Maximum and minimum irrigation diversions are indicated in Table 2, although, as for all offstream water uses, no operational constraints are enforced in this exercise.

Controlled flows from Mid Lake, minus Mid Valley consumptive use, and the Lower Fork tributary enter Lower Lake reservoir. There are two controlled releases from Lower Lake Dam, into powerplant D and into a canal that conveys water to a municipal and industrial demand area (M&I user) named Big City. Big City represents a transbasin diversion, from which no return flows are expected, as evidenced by the lack of a return link from Big City.

Figure 2 shows the names of the system components as entered by the user, as well as the numbers assigned automatically by the model to links and nodes (shown only for junctions and diversions). Although not apparent in Figure 2, links appear on the monitor in red or blue. Red links indicate locations in the network where decision variables are created by the model in order to formulate the water allocation problem.

Defining Demand Functions

To save space, hydropower demand functions are not presented here. Besides hydropower, the only other instream user competing for water in economic terms in the hypothetical basin is the water-based recreation area Tough Ride. This highly seasonal activity—it runs from May through September—is represented by linear demand functions of the form $P = a + bQ$. The seasonality can be inferred from the values of the coefficients of

the price functions given in Table 3, showing values different from zero only for the relevant months.

The two irrigation areas, Upper Valley and Mid Valley, have growing seasons running from April through October. The coefficients of the exponential demand functions for these uses—of the form $P = a e^{Q/b}$ —are shown in Table 3. Prices are set equal to zero for the non-irrigation months. For the transbasin urban demand zone, Big City, prices also decay exponentially with quantity supplied although—in contrast to the agricultural zone—municipalities and industries consume water all year around, as indicated in Table 3 by the non-zero values of demand function coefficients for all months of the year.

TABLE 3. Demand Functions for Instream and Offstream Demand Areas (Q in Mcm, P in \$/Mcm).

Month	-- Tough Ride --		--- Upper Valley ---		---- Mid Valley ----		----- Big City -----	
	a	b	a	b	a	b	a	b
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.	11,700.	-207.	71,200.	-134.
May	2000.	-2.0	40,000.	-749.	15,200.	-320.	76,000.	-145.
Jun	2000.	-2.0	40,000.	-814.	18,200.	-395.	79,600.	-155.
Jul	2000.	-2.0	40,000.	-857.	18,200.	-600.	85,000.	-164.
Aug	2000.	-2.0	40,000.	-890.	18,200.	-634.	83,100.	-160.
Sep	2000.	-2.0	40,000.	-749.	16,000.	-485.	73,400.	-141.
Oct	0.	0.	40,000.	-543.	12,700.	-358.	67,800.	-115.
Nov	0.	0.	0.	0.	0.	0.	56,700.	-88.
Dec	0.	0.	0.	0.	0.	0.	41,500.	-71.

Finding an Efficient Water Allocation

This section describes the water allocation for the hypothetical river basin that was found given the set of water prices and operational constraints partially described earlier. The problem was solved for a two-year period of analysis utilizing monthly time intervals. The optimization horizon was also set equal to 24 months. Only a minimum number of operational constraints were specified for the network, allowing the model to find a water allocation based almost exclusively on the value of water.

The flow cascading approach implemented in the current version of the model provides the *initial feasible solution* for the problem at hand. The approach consists of simply cascading flows through the reservoirs, avoiding storage regulation whenever possible, and assigning water to instream and offstream users provided that reservoirs' and water users' operational constraints are not violated (see Diaz and Brown, in press, for details).

The optimization algorithm SQP searches for the *final solution*—the optimal allocation of water—by successively solving quadratic programming problems. Figure 3 shows the evolution of the value of the global objective function as it progresses toward the optimal solution for the problem at

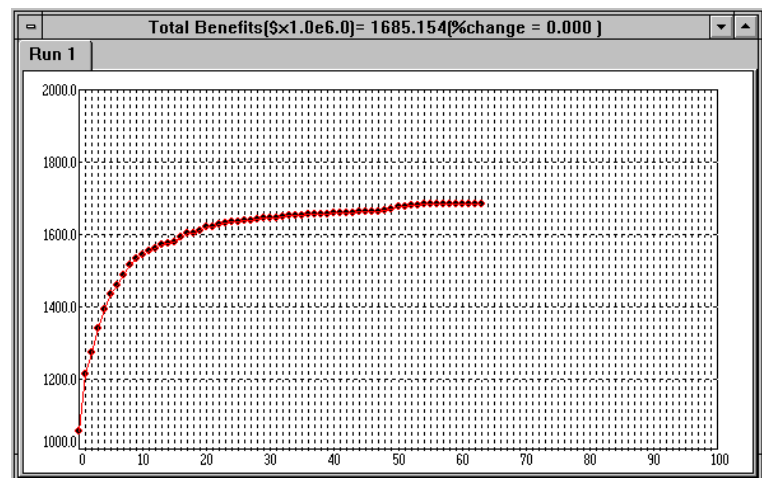


Figure 3. Evolution of the Value of the Global Objective Function.

hand. There is a substantial improvement in the allocation of water 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 take place during the remaining sequences. The search for the optimum is stopped either when the maximum number of sequences or the accuracy parameter is reached (both parameters are specified by the user). In this example, the accuracy parameter was binding; the model continued the sequential optimization until the difference in global return between two consecutive QP sequences was less than \$10,000, requiring 62 sequences to reach that point (Figure 3). At the optimum, the total revenues computed by the model amount to \$1,685.2 million over the two-year period.

Reservoirs, of course, play an important role during the process of allocating water in the basin, as flow regulation allows for the pattern of releases that efficiently satisfies instream and offstream demands. For example, Figure 4 shows the high contrast between the uncontrolled inflows and the controlled outflows from the West Lake reservoir.

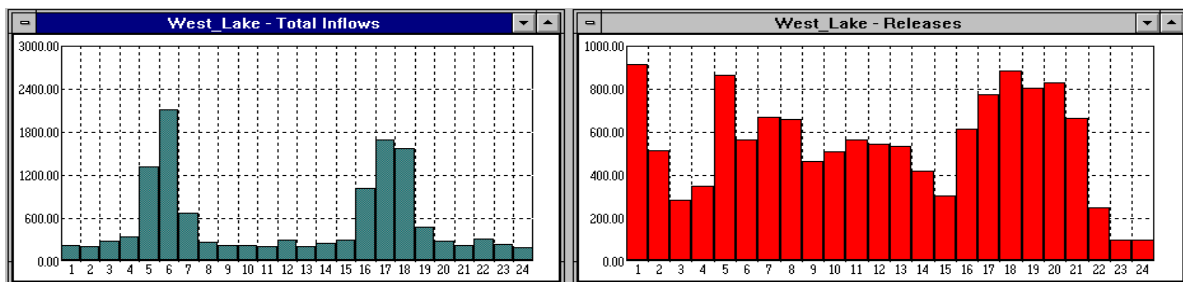


Figure 4. Inflows and Regulated Outflows from West Lake.

Figure 5 shows selected graphs of the result of the optimization. The two headwater reservoirs absorb most of the variability of the natural inflows, creating more 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 in an attempt to avoid spilling the large volumes of inflow associated with snow-melt runoff. Because Plants A and B are run-of-river plants, they impose no limitations in the oscillation of the water levels in the two headwater reservoirs. Contrarily, at Mid Lake Dam, where a variable-head powerplant is installed, almost constant—and maximum—water levels are maintained during the whole optimization horizon in order 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 significant regulation at the reservoir.

Water diversions into the Mid Valley irrigation zone are shown in Figure 5. The differing demand functions prescribed for each month of the growing season are alone responsible for the seasonal distribution of the allocated water, since, as pointed out earlier, no constraints were enforced for any instream or offstream water use during this exercise. The zero diversions during months outside the irrigation season are the result of specifying zero economic benefits for those months (see Table 3).

Optimal releases from Lower Lake are displayed by the stacked bar diagram in the lower right-hand corner of Figure 5. The lower bars correspond to water supplied to the Big City M&I demand area, whereas the upper bars represent water released for hydropower to Plant D. The seasonal variability in marginal prices assigned for Big City (see Table 3) translates into a pattern of water allocation with similar seasonality. Power releases from Plant D are small as the reservoir builds up storage, and then increase during the second year as more water is made available in the system.

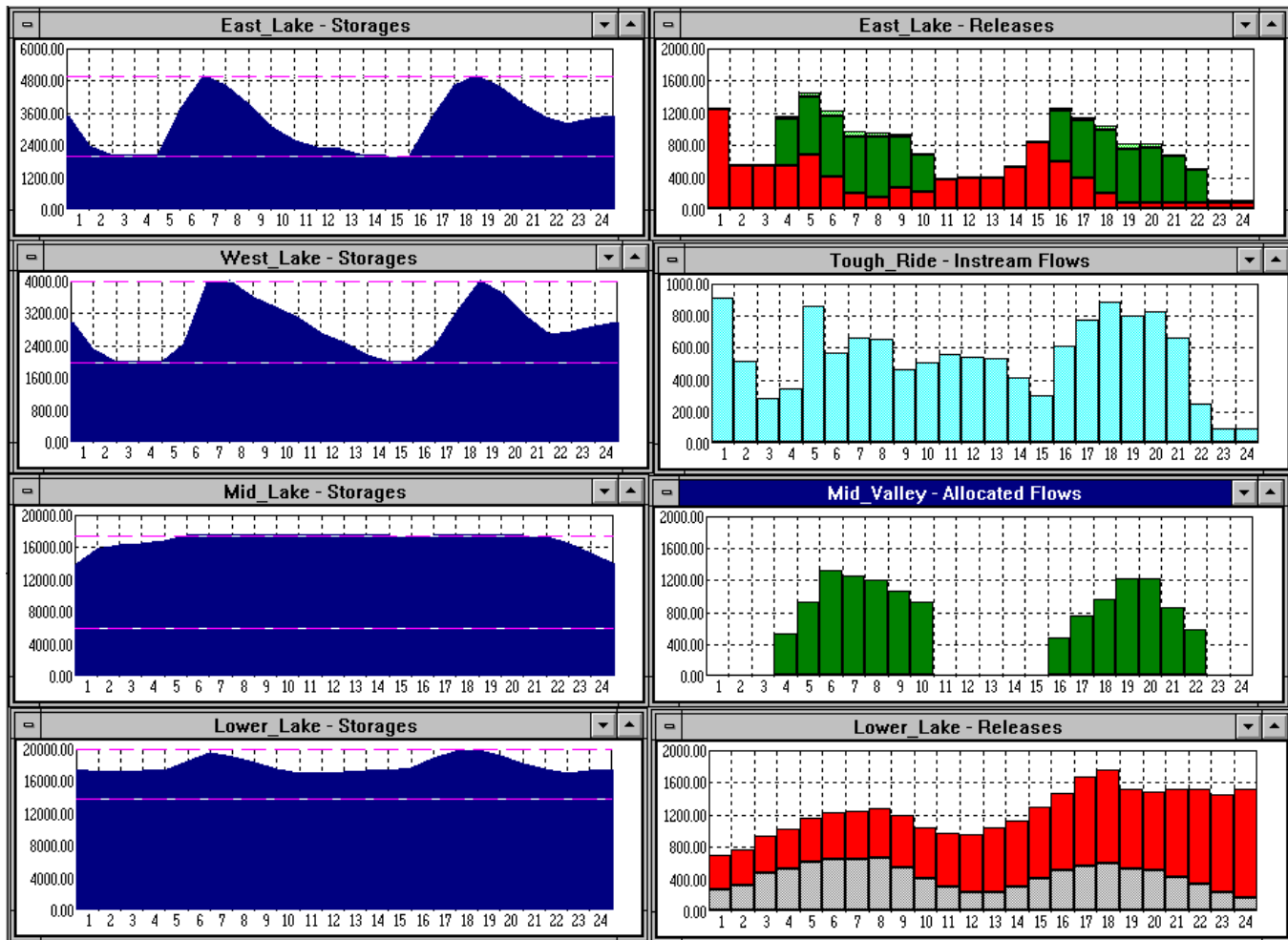


Figure 5. Selected Graphical Outputs from the Final Solution.

Releases from West Lake, after passing through Plant B, become instream flows in the West Fork River where the Tough Ride recreation area is located. Figure 5 indicates the effort made by the model to release relatively larger flows from West Dam during periods 5 through 8 and 17 through 20, the months during which rafting occurs. The upper bar graph in Figure 5 shows the releases from East Lake. Optimal flows for Upper Valley display the classical seasonality of irrigation demand, whereas Plant A releases are more uniformly distributed over the optimization horizon (they tend to follow the storage fluctuations in the reservoir). 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, as the optimization algorithm gives preference for releases to the users generating revenues.

Evaporation losses represent a small amount of water when compared to the total inflows to the reservoirs. The maximum losses occur at Lower lake, approximately 2 percent. It is clear that evaporation losses do not influence the storage patterns. Reservoir spillages do not occur for the period of record analyzed in this exercise.

Changes in Offstream Water Demand

The allocation of water to the offstream demand areas (irrigation and M&I) for the demonstration above relied exclusively upon the demand curves specified for each time period. For instance, the optimal allocation for Mid Valley, shown in Figure 5 (third bar graph), displays a seasonal variability consistent with the monthly demand functions specified in Table 3. We now introduce a change in the demand of water from an offstream

zone; demonstrate how the new problem can be solved with minimum computational effort; and discuss the implications of the change. Suppose flows are required for one of the non-irrigation months—say January—at Mid 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 constraint. While for the baseline case the demand function had null parameters for the month of January (see Table 3), we make them now equal to the values for April ($a=11,700$ and $b=207$).

The user can solve the "new" water allocation problem from scratch, by altering the marginal price of water at Mid valley for the month of January, validating the network's connectivity, finding a new initial feasible solution, and finally solving the optimization problem that finds efficient water allocation policies under the new economic condition. However, because changes in the structure of prices *do not invalidate feasibility* in the network, the user has the option to proceed from the last optimal solution to reach the new optimal condition.

Changes in marginal prices can be introduced at any time during the execution of the optimization, as well as at the end of the sequences. If the change is introduced as the application is executing, the user will see—using the graphical outputs—how the model immediately starts redirecting the allocation of water to accommodate the new economic conditions. If the change is introduced once AQUARIUS has reached an optimum, the model will adopt the last optimal solution as the initial feasible solution for the new round of optimization. For a minor change in price as in this example, the model will find the new optimum very quickly.

Figure 6 shows the results of the above outlined procedure. The water allocation at Mid Valley now shows positive flows for the month of January (for comparison with the baseline solution, see Figure 5). The allocation of flows to Mid Valley during the month of January reflects the willingness of the irrigation area to compensate the system for the extra water that it is demanding for that month. In other words, a new Pareto optimal arrangement was found.

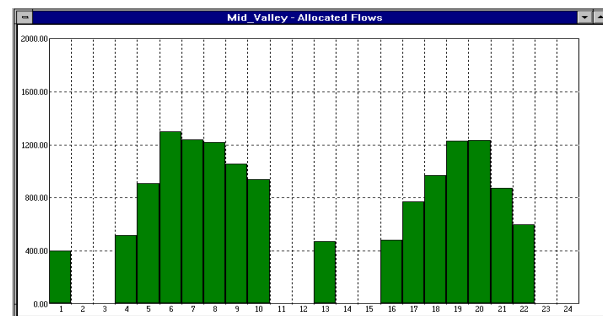


Figure 6. Change in Offstream Water Demand.

As another example of *what if...* scenarios—this time a change in physical, rather than economic, data—consider an improvement in irrigation efficiency. Either by structural measures or conservation practices, the water duty for irrigation often can be decreased. While consideration of this new scenario may imply several modifications to the original case, here we will simply increase the amount of return flow that originates from the Upper Valley irrigation area, from the old value of 0.5 to the new value of 0.7. This has practically the same effect on the network as reducing the water duty, as more water will be left in the river for use by other system components downstream.

After solving the network with the return flow change (note that when a physical variable is changed a new initial feasible solution is required), the benefit stemming from the operation of the network increases from \$1,685.2 mill. to \$1,712.5 mill., a \$27.3 mill. (1.6 percent) change over the two-year periods. Additional information can also be extracted to identify the downstream water uses who benefited from this improved economic condition. The increase in benefit opens up the possibility of negotiations among the multiple users in the basin to finance the structural improvements necessary to conserve water in the basin.

WORK IN PROGRESS

As discussed earlier, water allocations achieved using Version 96 of the model maximize economic efficiency. Under the dominant water allocation doctrine in the western United States—the *prior appropriation doctrine*—water is allocated following a time-based priority rule, whereby the water available to satisfy a new application is reduced by the sum of all prior established rights. A time-based allocation in a heavily appropriated river can become *inefficient* as values change if—as is commonly the case with water—institutional

barriers or market failures impede voluntary transfers of rights from lower-valued to higher-valued uses. Thus, actual water allocations in the West may be quite different from the economically efficient allocations achieved using V.96.

In order for AQUARIUS to predict allocations under current or alternative priorities and operating rules, a simulation facility is presently being added to the model. An attractive tool for achieving such simulation is a *network-flow* model. Simulation models based on network-flow programming constitute a “hybrid” formulation that combines some advantageous features of simulation with some optimizing capability. The object-connectivity capabilities of AQUARIUS are fully exploited to couple data requirements of the network flow algorithm to the topology of the river basin to be modeled. The network-flow solver—to be available in V.97—will be an alternative “engine” to the fully dynamic optimization algorithm already implemented in V.96.

Regardless of the process by which the existing allocation of water in a basin became established, it may be helpful to compare the *current allocation* with an *efficient allocation*. Such a comparison may indicate promising opportunities for private water trades, or, where such trades are hampered or precluded by institutional barriers, may indicate areas where institutional reforms can allow a more efficient water allocation to occur. Also, where water developments are publicly financed, the comparison may indicate directions that the public entity should consider to increase the efficiency of the public project. V.96 facilitates such comparisons by characterizing an efficient allocation—subject, of course, to the analyst’s ability to specify demand functions for the key water uses. The simulation capability envisioned for V.97 will, by simulating the current allocation within the same modeling structure as that used to articulate an efficient allocation, allow a more direct comparison of the simulated current allocation with the efficient allocation.

LITERATURE CITED

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