

PLANNING WATER ALLOCATION IN RIVER BASINS, AQUARIUS: A SYSTEM'S APPROACH

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INTRODUCTION

Concern for the environment, demand for outdoor recreation, and interest in sustainable development are redefining how water is stored and distributed in river basins. In particular, tradeoffs between instream and offstream water uses have become increasingly important in planning and managing water resources. These tradeoffs are important in new water developments as virtually all water projects have an impact on recreation and environmental quality. However, they are also important for existing water developments, especially when they are reevaluated for license renewal. Such concerns require modeling to determine how water used for traditional activities and that used for nontraditional activities affect each other.

Most water management systems were designed and are typically operated for traditional water uses, including flood control, hydropower, irrigation, and urban water supply. Nontraditional uses include preserving the geomorphological and biological integrity of a river, as well as providing opportunities for water-based recreational activities. Similar to the systems they were designed to analyze, river-basin models have focused on traditional water uses. Even multipurpose operation models usually included only traditional purposes such as hydropower and diversions to farms or cities. Nontraditional water uses, to the extent they were incorporated in models, were considered of secondary importance. The degree that nontraditional water uses have been incorporated into river-basin models has been limited by the perceived lower importance of nontraditional uses, lack of knowledge about geomorphology and riparian ecosystems, and by the difficulty of measuring the benefits of nontraditional uses.

The values of most traditional uses are quantifiable in terms of a benefit function that relates resource availability to the benefits generated. However, benefits of nontraditional uses were generally not estimable in units commensurate with the traditional uses, so they were often omitted from quantitative reservoir analyses and operations. Over the past 30 years, the increasing value of outdoor recreation and other amenities has encouraged economists to develop techniques to estimate the economic value of nonmarket goods and services. These methods have been applied to water uses including activities that rely on instream flow. This has created the

opportunity for enhanced models of water systems that provide continued support of the traditional demands and also recognize nontraditional water uses for environmental, recreational, and aesthetic objectives.

Over the same period of time, systems engineering, and in particular mathematical modeling, have increasingly been used for design, planning and operation of complex water resource systems. During the planning stage, mathematical models allow decision makers to evaluate the physical and economic impacts of existing and alternative structural measures, changes in allocation policies, increased demand levels, and new environmental and institutional restrictions.

Rogers and Fiering (1986) maintain that the most valuable role of systems analysis in water allocation is generating viable new alternatives to solve water allocation problems. The key concept is *generation of new alternatives* rather than using the computer to track sequences of hydrologic input through the current system, which only examines existing operation rules. The series of alternatives, whose characteristics might be distinct, may form the basis of negotiations to determine a new allocation. When the analysis allows for new alternatives, the techniques of systems analysis have the potential of significantly improving water resources planning and management.

This paper describes AQUARIUS, a state-of-the-art computer model devoted to the temporal and spatial allocation of flows among competing water uses in a river basin. The model is dedicated to the analysis of increasingly complex water systems, systems that not only continue support of the traditional water uses, but also recognize nontraditional uses for environmental and recreational objectives. This paper provides a succinct description of the model and its capabilities. A comprehensive description of the model is presented by Diaz et al. (2002).

EFFICIENT WATER ALLOCATION

AQUARIUS is driven by an economic efficiency criterion that calls for reallocating stream flows among traditional and nontraditional uses, subject to specified constraints, until the net marginal economic returns in all water uses are equal. This equality occurs because, if marginal values differ and demand curves are downward sloping, a higher-valued use can theoretically afford to purchase water from a lower-valued use, paying a price that exceeds the water's value in the lower-valued use. Transfers from lower-valued to higher-valued uses continue until the advantages of trade are eliminated, that is, until marginal values are equal and an optimal allocation is reached. We adopted an economic criterion for determining an optimum primarily because economic demands have traditionally played a key role in water allocation decisions and because economic value estimates for some nontraditional water uses are now becoming available.

Demand functions are not easily estimated from market data. At any one time, all that is observed is one point along the demand curve, which is one price-quantity combination among a large number of combinations that could be observed under different conditions. However, by

various techniques, including observation of different real-world markets containing similar people in different supply situations, economists have learned about demand functions. Typically they find that as the price decreases the quantity consumed increases, yielding a downward sloping demand function (though demand curves faced by individual firms may be horizontal).

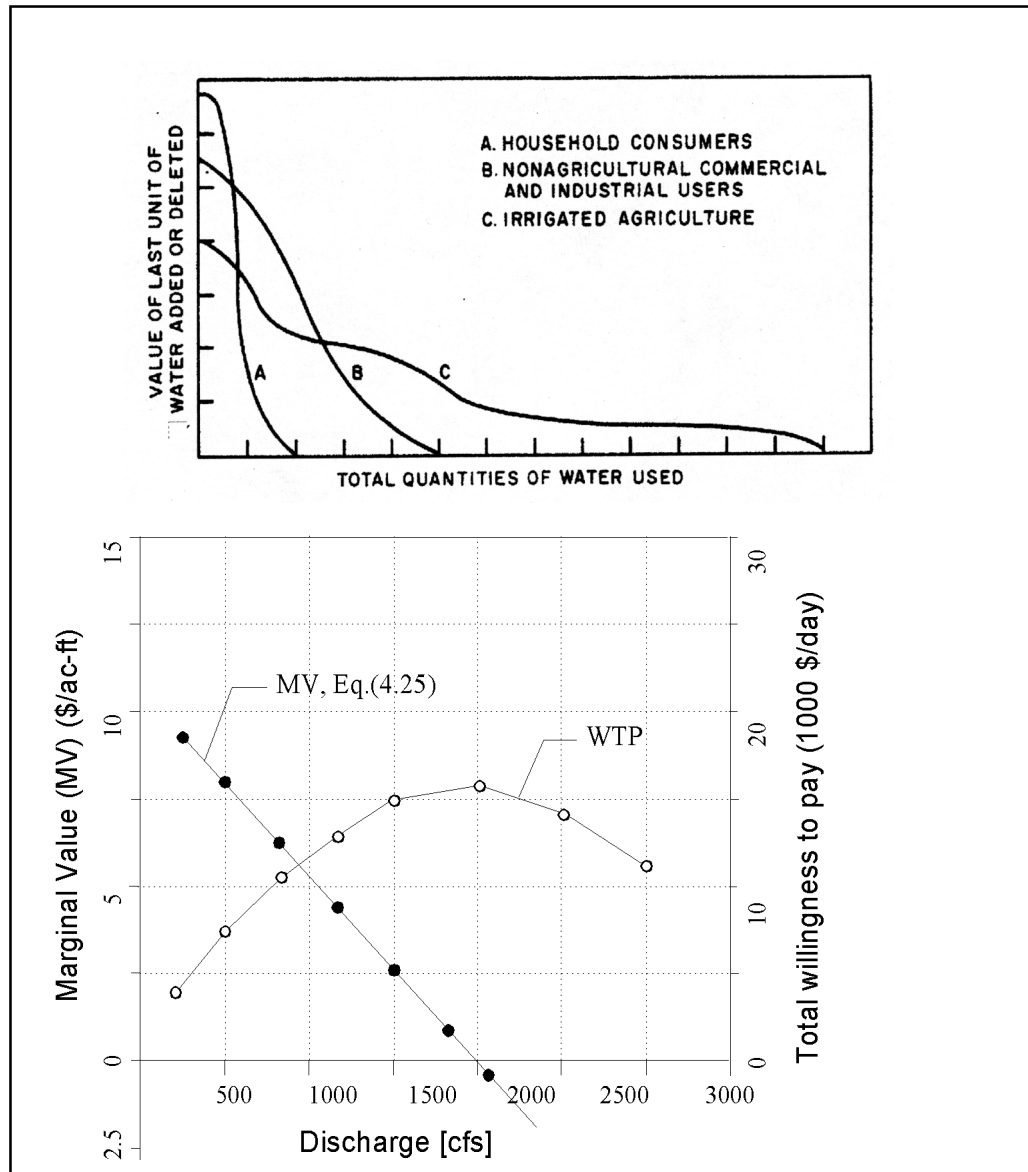


Fig.1 Top: offstream demand curves (after Kelso et al, 1973); Bottom: marginal and total recreation value as a function of instream flow (after Duffield et al, 1992).

In AQUARIUS, each traditional water use (hydropower, agriculture irrigation, municipal and industrial water supply, flood control) and nontraditional water use (instream recreation, lake recreation) is represented by a demand curve, also known as marginal benefit curve, indicating the maximum price that the user is willing to pay to acquire each additional unit of water. AQUARIUS accommodates both downward sloping and horizontal demand curves. In addition, two system components, flood control and ground water pumping, generate losses (costs) rather than benefits in a flow network. These costs are interpreted in the formulation as negative benefits. Examples of demand curves are shown in figure 1 for offstream demands (urban and industrial demand, agriculture irrigation) and instream recreation.

The model solution will indicate society's marginal willingness to pay for water given the optimal water allocation, subject to the constraints imposed on the solution. For a water use with a predetermined level of allocation but without a defined economic demand function (such as the value of protecting an endangered fish species), the analyst can either constrain the model to meet the specified allocation or experiment with surrogate demand curves until the required level of water allocation is reached. The latter approach indicates the level of economic subsidy required to provide the incremental increases of flow to sustain the use in open competition with other uses. The interactive nature of AQUARIUS facilitates such experimentation.

SOLUTION OF THE WATER ALLOCATION PROBLEM

In modeling an actual allocation problem, it is imperative that problem formulation, particularly the objective function, retain the essential characteristics of the system being modeled. Realistic conceptualization of a water allocation problem typically requires relatively complex model formulations. A common source of this complexity is the nonlinear nature of production and benefit functions. Nonlinear optimization problems are commonly encountered in water resources applications. Besides the nonlinearities introduced in the model by hydroelectric power production, the economic benefits of several different water uses are best represented by nonlinear benefit functions as shown earlier.

In AQUARIUS, water allocation throughout a system and for an entire planning horizon is based on a global objective that maximizes the sum of all economic benefits from instream and offstream water uses. Hence, what remains is to combine the individual benefit functions B into a total benefit function TB that reflects all water uses j in the basin and all time periods i in the planning horizon. The overall objective is to maximize the total benefit function TB , also expressed as $f(\mathbf{x})$:

$$\underset{\mathbf{x}}{\text{maximize}} \quad TB(\$) = \sum_{i=1}^{np} \sum_{j=1}^{nu} \int_0^{a_{ij}} f_{ij}(x_{ij}) dx_{ij} \quad (1)$$

where $\mathbf{x}$ denotes the set of control variables, nu is the number of water uses generating revenue in

the basin, and np is the number of time periods (optimization horizon).

Equation (1) considers benefits from all water uses, plus the losses stemming from flooded river reaches (a negative benefit), plus the pumping cost of ground water supply (another negative benefit). Other costs of water use, such as the cost of operating a hydroelectric plant or of constructing an irrigation canal, are not explicitly considered in the model. The model could be used to evaluate net benefits (i.e., the difference between benefits and costs) by subtracting costs directly from the benefits in the individual benefit functions, essentially making each benefit function a net benefit function.

The problem is to maximize the general nonlinear objective function (1) subject to physical, operational, and environmental restrictions such as:

- C max/min ground water pumping,
- C reservoir storage limits,
- C firm water supply,
- C seasonality of water supply,
- C max/min instream flows,
- C max/min offstream diversions.

Except for the nonlinear objective function, the problem above is similar to a standard linear programming problem. The function $f(\mathbf{x})$ can be any type of nonlinear function subject to the requirement of being continuous and differentiable. In summary, the objective function and constraints are represented by mathematical expressions as a function of the control variables.

The solution technique implemented in AQUARIUS for solving the above problem 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. Although a quadratic function is the simplest nonlinear approximation that can be used for a nonlinear objective, it is suitable for solving multi-reservoir optimization problems with hydropower generation and nonlinear demand functions. Furthermore, model development indicated that, because of the particular structure of the water allocation problem, a quadratic approximation of the objective function is advantageous from the computational viewpoint, allowing a fast convergence to the optimal solution (Diaz and Fontane, 1989).

The method approximates the original nonlinear objective function with a quadratic equation using Taylor series expansion and then solves the problem as a quadratic programming (QP) problem. Starting with an initial feasible solution, $\mathbf{x}^0$, the algorithm carries out a Taylor series expansion on the nonlinear objective function around the given initial solution, retaining the first and second order terms to form a quadratic function. The optimal solution obtained by standard QP is only true for the approximated objective function. Because the optimal values of the variables may differ from the initial values upon which the approximation of the nonlinear quadratic objective function was based, it is necessary to repeat the process using the new values for the set of variables as the starting point for the next round of the sequential solution. A succession of these approximations is performed until the solution of the quadratic programming

problem reaches the optimal solution, which is when successive optimal values do not differ by more than the stipulated tolerance limit, or when the maximum limit on the number of iterations is reached. The sequential procedure of successively solving quadratic programming problems, known as Sequential Quadratic Programming, can effectively handle the physical and economic nonlinearities found in real-world water resources allocation problems.

MODELING THE RIVER SYSTEM

A model is a conceptualization, and a simplification, of a real-world system. The degree of detail with which each component is characterized varies with the desired accuracy. For a model to reflect the real behavior of a system with sufficient accuracy to evaluate real world alternatives, it must preserve all the essential operational characteristics of the river basin. For a generalized model, such as the one proposed here, this is a challenge.

AQUARIUS' software architecture was developed using the latest advances in programming languages (C++, an object-oriented programming (OOP) language), and was provided with graphical interfaces to simplify specifying the river basin components, entering the data, and interpreting the results. Water systems are ideal candidates for modeling under an OOP framework, where each system component is an object in the programming environment. A water system may include different types of water components, including water sources, reservoirs, powerplants, diversions or junction points, irrigation areas, urban demand areas, environmentally-sensitive river reaches, etc., which can be interpreted as objects of a flow network in which they interact. The latest version of the model (Version 2002) supports the following water uses and control structures:

- Flow regulation (storage reservoir)
- Surface water supply (undeveloped basin)
- Ground water supply (pumping well)
- Water diversion (diversion structure)
- Water junction (junction point)
- Conveyance structures (river reach, canal, pipeline)
- Flood control (river reach)
- Hydropower generation (powerplant)
- Agriculture irrigation (demand zone)
- Municipal and industrial water supply (demand zone)
- Instream recreation (river reach)
- Lake recreation (reservoir)
- Instream flow protection (river reach)

Hydraulic and Mathematical Connectivity

Solving the water allocation problem for any user-defined network requires an automated procedure to handle the formulation mathematics. The mathematical connectivity of a river network should build up the optimization model that in turns solves the water allocation problem (in our case a set of operational constraints and assemblage of the gradient vector and Hessian

matrix of the second order approximation of the total objective function). These tasks required the development of an algorithm capable of automatically gathering information from the network about system components and flows, both “controlled” and “uncontrolled,” occurring upstream and downstream from a given system component. In AQUARIUS, the mathematical connectivity of the system components is derived automatically from the linkage of the objects comprising the network, which in turn reflects the direction of flow from one structure to the next (i.e., their hydraulic connectivity). In other words, the way water sources, storage reservoirs, and demand zones are arranged in a river basin (i.e., network topology) determines the hydraulic and mathematical dependence among them.

An idea of the intricacies of mathematical connectivity is portrayed by in figure 2, showing schematically all possible inflows to and outflows from a storage reservoir. The purpose of a storage reservoir is to transform the random and periodic nature of flows into a series of releases that more closely correspond with the seasonal water demands in a river basin. This objective is achieved by regulating the amount of stored water and by passing flows through the reservoir outlet works and spillway to meet downstream water supply functions and to minimize flood damages. Flow regulation takes an uncontrolled flow, such as water flowing naturally from an undeveloped upstream basin, and turns it into controlled releases from a reservoir to satisfy a particular demand.

- XI = controlled inflows
- d^u = upstream decision variable

- UI = uncontrolled inflows
- NF^u = upstream natural flows
- L^u = upstream reservoir spillage

- XR = controlled releases
- d = decision variable

- UR = uncontrolled releases
- L = reservoir spillage
- E = reservoir evaporation

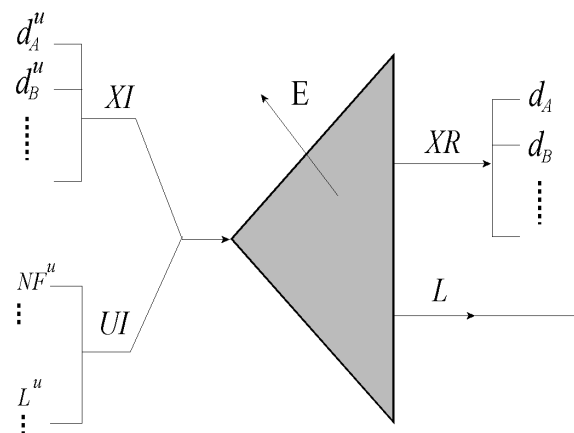


Fig.2 Variables to describe storage dynamics in a reservoir.

In figure 2, any upstream controlled flow, d^u , that reaches the reservoir under consideration becomes a controlled inflow to that reservoir. If several d^u flows exist, they are all grouped under the term XI . Spillage from upstream reservoirs L^u and natural flows NF^u are considered uncontrolled inflows to the reservoir and are grouped under the term UI . As with d^u , the inflow variables L^u and NF^u may be indicative of one or more sources of flow. Note that all inflows with the superscript $(^u)$ originated upstream from the reservoir under consideration. Controlled and uncontrolled flows occurring upstream from a given node influence the decisions at that node.

Among reservoir outflows, we present two groups: the controlled releases d and the uncontrolled reservoir releases, such as spills L and evaporation losses E , grouped under the term UR (not depicted in figure 2). As more than one controlled release d is possible, we group them under the term XR . Controlled releases encompass water for offstream and instream uses downstream from the reservoir, such as hydropower, municipal water supply, irrigation demand areas, instream recreation, etc. We should mention that the model includes an alternative formulation of reservoir evaporation in which evaporation losses are modeled “explicitly” in the formulation of the reservoir dynamics. This more elaborate formulation gives the model the capability to anticipate periods with extreme evaporation losses and affect the operation of reservoirs accordingly.

Creating a Flow Network

The user interacts with the model through the so-called network-worksheet screen (NWS), figure 3, which allows the analyst to readily create the river basin network of interest, thanks to 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 properties tool palette.

During the creation of the flow network, each system component (object) corresponds to a graphical network node. These nodes are represented by icons, which are a pictorial representation of the object. By dragging one of these icons from the menu, the model creates an instance of the object on the screen. This procedure also allows the user to connect graphically the input slots of this object with the output slots of one or more objects. In modeling terms, a physical link (e.g., a river reach) connecting two system components becomes an outflow slot of the upstream object connected to an inflow slot of the downstream object. While in the NWS, this operation is carried out by simply left-clicking on the outgoing terminal of the upstream object and then on the incoming terminal of the other object. This procedure greatly facilitates the assembling or alteration of water systems by simply “wiring up”(hydraulic connectivity) their system components in the NWS.

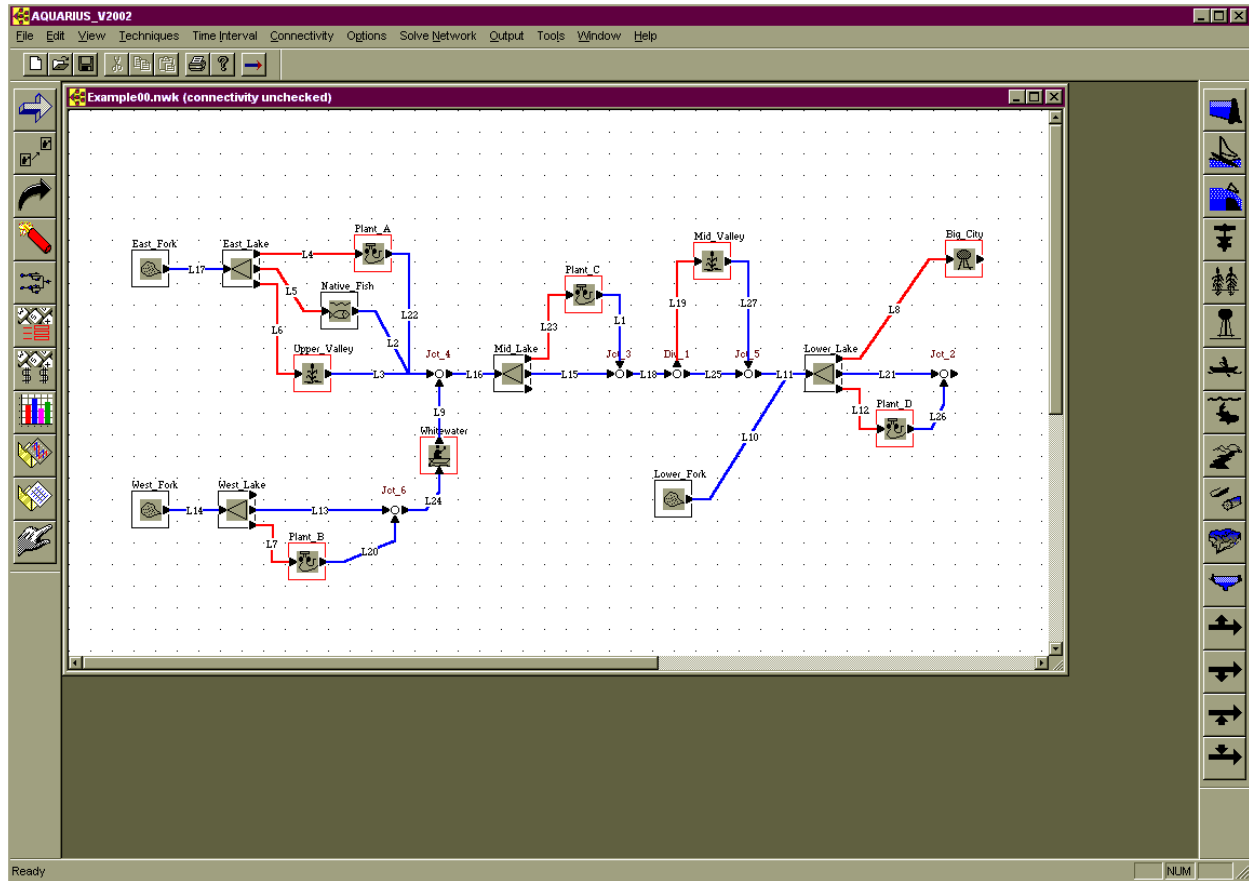


Fig.3 AQUARIUS network worksheet screen (Version 2002).

Entering Input Data

The model's input data consist of physical and economic data. By clicking on the icon, the object displays data slots for input and output and also allows the user to visually inspect for incorrect or missing data. The physical data include the information associated with the dimensions and operational characteristics of the system components, such as maximum reservoir capacity, percent of return flow from an offstream demand area, and powerplant efficiency. 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.

Solving the 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. The problem is solved in two steps. First, an initial feasible solution (IFS) to the water allocation

problem is obtained automatically by the model. The IFS that the model finds will generally be far from the optimal solution but serves as the starting point for the sequential optimization procedure (SQP) that follows. The second step, actual optimization, consists of running an optimization algorithm to find the optimal solution of the water allocation problem. As explained earlier, a sequential algorithm goes through a succession of quadratic approximations of the nonlinear global objective function until the optimal solution is reached.

The user can track the sequential changes in system state and decision variables during the optimization. Flow networks in general contain a myriad of state, decisions and economical variables that the analyst may need to consider. AQUARIUS facilitates the interpretation and analysis of all that information through readily accessible graphical and tabular output display formats.

Other Aspects of the Model

Although the present version of the model implements only a monthly time step (because of graphical user interface restrictions), AQUARIUS was conceived to simulate the allocation of water using any time interval, including days, weeks, months, and time intervals of nonuniform lengths. The model 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 system operation, and the *optimization horizon*, used to specify how far 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 a water allocation problem entirely within the domain of the objective function allows the user to redirect the water allocation process in any direction in real time, directly from the screen, as the optimization progresses. This unique feature provides an expeditious and innovative mode of exploring *what if...* scenarios.

ACTUAL AND EFFICIENT WATER ALLOCATION

Existing water allocations have developed under systems of water rights. In the United States those rights have centered on either the Riparian or the Prior Appropriation Doctrine. The Prior Appropriation Doctrine has been prevalent in drier regions of the U.S. where there is often insufficient water to meet all use requests and where careful modeling of water storage and allocation is most necessary. Under this doctrine, water is allocated according to a time-based priority rule whereby the water available to satisfy a new application is reduced by the sum of all prior established rights. Thus, only the remaining unappropriated flow is available to satisfy new applications. In some streams, late appropriations are left with little flow, especially in drier years.

A priority-based allocation in a heavily appropriated river can become inefficient as values

change if institutional barriers impede voluntary transfers of water or water rights from lower-valued to higher-valued uses. Because institutional barriers commonly affect Western water, actual water allocations may be different from the economically efficient allocations achieved using AQUARIUS. It may be helpful to compare the actual 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 for a more efficient water allocation. Where water developments are publicly financed, the comparison may indicate directions that the public entity should consider to increase the efficiency of the project. AQUARIUS facilitates such comparisons by characterizing an efficient allocation, subject to the analyst's ability to specify demand functions for the key water uses.

SOFTWARE DEMONSTRATION AND AVAILABILITY

The software runs on a personal computer under the Microsoft Windows 32-bit operating system. Enhanced performance is attained using a system with high number crunching capabilities. The latest distribution of the program AQUARIUS (Version 2002), together with its technical documentation, can be downloaded from the World Wide Web by visiting the AQUARIUS web-page at: <http://www.fs.fed.us/rm/value/aquariusdwnld.html>. Usage is free for government agencies and for teaching and research purposes. Chapter 8 of the documentation includes examples of use of AQUARIUS to model a hypothetical basin.

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