

AQUARIUS: A GENERAL MODEL FOR EFFICIENT WATER ALLOCATION IN RIVER BASINS

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ABSTRACT

This paper introduces AQUARIUS, a state-of-art computer model devoted to the *temporal* and *spatial* allocation of water among competing uses in a river basin. Version 96 of 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; that is, until a Pareto optimal arrangement is reached. This is achieved by systematically examining—using nonlinear optimization—the feasibility of reallocating unused or marginally valuable storage and releases in favor of alternative uses. Because water systems components can be interpreted as objects of a flow network in which they interact, the model considers each component of a water system as an equivalent node or link in the programming environment using an object-oriented programming language (C++). Future versions will allow simulation of existing allocation rules and priorities.

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 for a host of environmental and recreational objectives. 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 geomorpho-logical integrity of a river, as well as provision of opportunities for water-based recreational activities such as fishing and boating.

This paper introduces AQUARIUS, a state-of-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 in a river basin. 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. Documentation of the model can be found in Díaz and Brown (in press).

THE 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 Pareto optimal arrangement is reached. Each traditional use (e.g., hydropower) and nontraditional use (e.g., water recreation) is represented by a *demand curve*, also known as marginal benefit function. An example of this type of curve is shown in Figure 1 for instream recreation in the Bitterroot River in Montana, involving dry fly fishing, floaters and shoreline recreationists.

Because—in contrast to Figure 1—nonlinear demand curves are more the rule than the exception, AQUARIUS uses exponential models of the form $P = a e^{Q/b}$, with $a > 0$ and $b \neq 0$, 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 *pre-determined* but for which the demand function (in economic terms) is practically impossible to define, the analyst can experiment with surrogate demand curves until the required level of water allocation for that particular uses is satisfied. Indirectly, this approach indicates the societal willingness to pay for incremental increases of flow for nontraditional water uses, or perhaps, the level of economic subsidy required to sustain that activity in open competition with other uses in the basin.

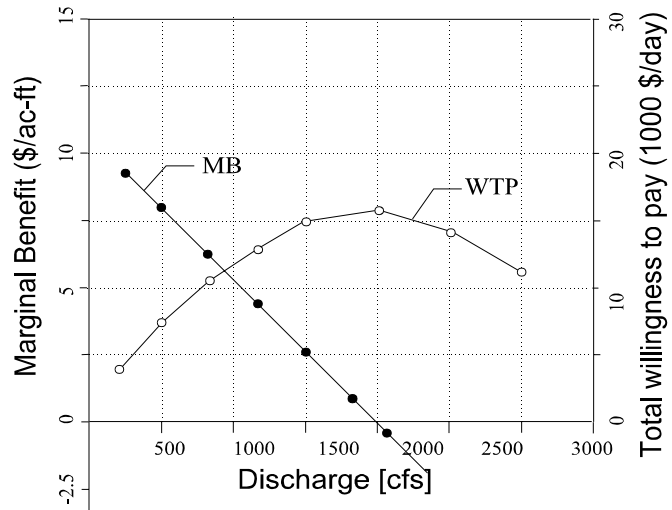


Fig.1 Marginal and total recreation value as a function of instream flow (Duffield et al., 1992)

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 benefits* stemming from the instream and offstream use of water—as expressed by their willingness to pay—subject to the operational constraints of the system such as: reservoir storage limits, firm water supply levels, max/min instream flows, max/min diversions, seasonality of water demands, etc. Given demand functions for the various water uses j , the global benefit function (B) to be maximized over the various time periods i is

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

np : total number of time periods
 nu : total number of water uses

where x is the level of output in the demand function $f(x)$ and a denotes the level of allocation. It should be remembered that B is maximized when a_{ij} are set such that the marginal prices are

equal for all i, j . 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 (provided that an unconstrained solution to the allocation problem is found). 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 dealing with the solution to 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—until the solution of the quadratic problem reaches the optimal solution. This method of solution is an extension of the work reported earlier 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 (each reservoir, demand area, diversion point, etc.) is conceptualized as an equivalent object in the programming environment.

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 a graphical node or link (object) 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 on the outgoing terminal of a node, and next into the incoming terminal of the other 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)

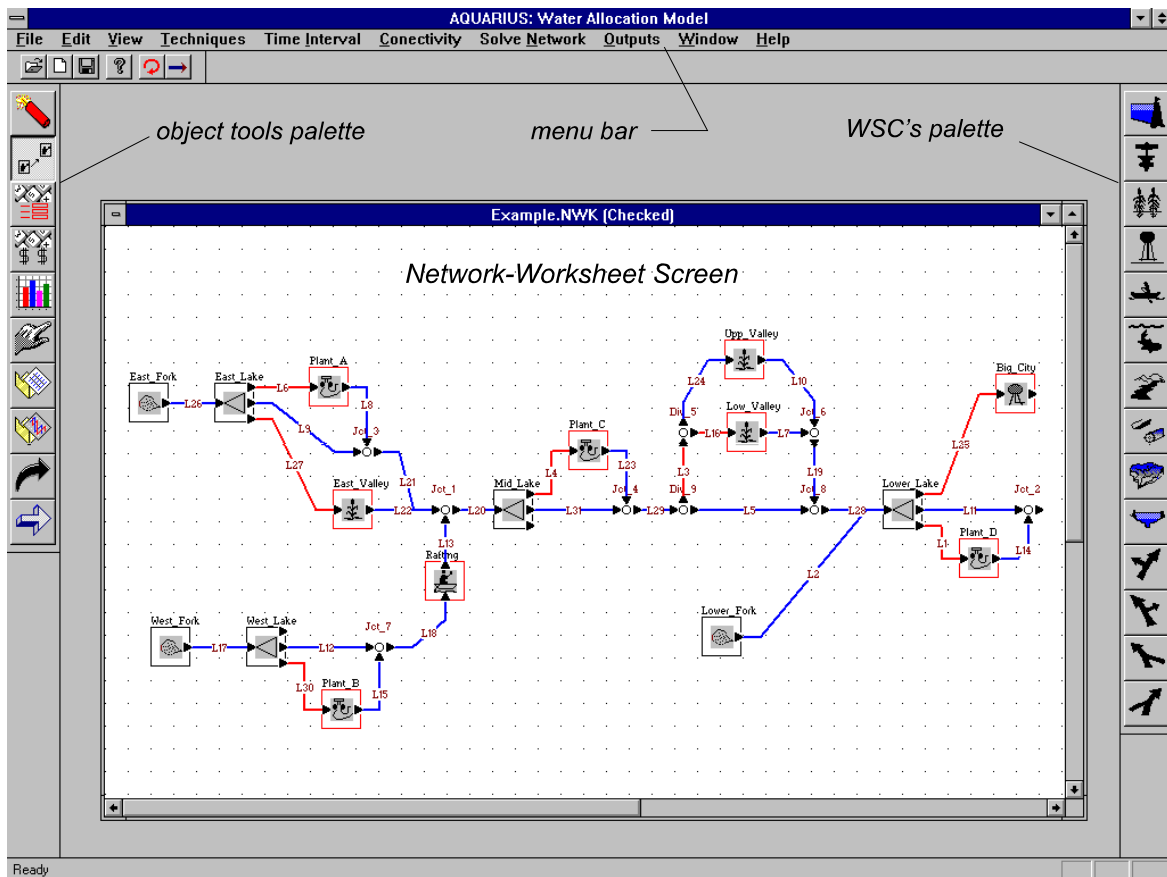


Fig.2 AQUARIUS Network-Worksheet Screen

ENTERING INPUT DATA

The input data to the model 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.

SOME OPERATIONAL ASPECTS

AQUARIUS was conceived to simulate the allocation of water using any time interval of analysis: daily, weekly, monthly. Future versions of the model will also support time intervals of non-uniform 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.

The user can use AQUARIUS in a full deterministic optimization mode (for general planning purposes), or in a quasi-simulation mode, with restricted foresight capabilities. For that purpose, 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 (and optimize) 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. 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 several *what if...* scenarios.

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. Because of space limitations in this paper, a case study has not been included. The software runs on a personal computer under a Microsoft Windows 95 or Windows NT operating system.

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.

LITERATURE CITED

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