United States
Department of Agriculture

Forest Service

Rocky Mountain
Forest and Range
Experiment Station

Fort Collins,
Colorado 80526

General Technical
Report RM-GTR-299
Revised for Aquarius version 2000

AQUARIUS: A Modeling System for River Basin Water Allocation

Gustavo E. Diaz
Thomas C. Brown
Oli Sveinsson

Diaz, Gustavo E.; Brown, Thomas C. And Oli Sveinsson, 1997 (last revision August 2000). Aquarius: A modeling system for river basin water allocation. General Technical Report RM-GTR-299. Fort Collins, CO: U.S. Department of Agriculture, Forest Service, Rocky Mountain Forest and Range Experiment Station. 172 p.

Abstract

This report 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 requiring the reallocation of stream flows until the net marginal return in all water uses is equal. This occurs by systematically examining, using a nonlinear optimization technique, the feasibility of reallocating unused or marginally valuable water storage and releases in favor of alternative uses. Because water-system components can be interpreted as objects of a flow network, the model considers each component as an equivalent node or structure in the programming environment as well. This is done using an object-oriented programing language (C++). The report contains a comprehensive description of the development of Aquarius, including how to use it and examples of its use.

Keywords: water allocation, economic efficiency, object-oriented programming, river-basin planning, economic demand, nonlinear optimization

Acknowledgments

We are grateful to Venkata Gudanti, Hatim O. Sharif, and Oli Sveinsson, graduate students at Colorado State University, who assisted with formulating and programming of the model. We thank Hubert Morel-Seytoux, James Booker, and John Duffield for their helpful reviews of the manuscript.

USDA Forest Service
General Technical Report RM-GTR-299

Modified August, 2000

AQUARIUS: A Modeling System for River Basin Water Allocation

Gustavo E. Diaz
Colorado State University

Thomas C. Brown
USDA-FS, Rocky Mountain Research Station

Oli Sveinsson
Colorado State University

Contents

	Executive Summary	vi
Chapter 1	**Introduction**	1
	Modeling River Basin Systems	1
	Objectives	4
	Report Organization	5
Chapter 2	**Efficient Water Allocation**	7
	Current Water Allocation Systems	7
	Economic Efficiency	8
	Economic Demand Functions	10
	Irrigation Water Use	13
	Shape of the Annual Demand Curve for Irrigation Water	14
	Representative Annual Irrigation Water Demand Curve	18
	Demand for Raw Water	19
	Monthly Distribution of Annual Demand	20
	Municipal Water Use	21
	Shape of the Annual Demand Curve for Residential Water	22
	Representative Annual Demand Curve for Residential Water	24
	Commercial Water Use	25
	Demand for Raw water	26
	Monthly Distribution of Municipal Demand	26
	Industrial Water Use	27
	Hydropower	28
	Water Demand Curve in Hydroelectric Energy Production	29
	Riparian Recreation Water Use	30
	Shape of the Demand Curve for Instream Flow for Recreation	31
	Demand Monthly Distribution	33
	Nonuse Values	33
	Aggregate Consumptive Water Demand	34
	Final Remarks	35
Chapter 3	**Modeling of System Components**	37
	The River Basin System	37
	Storage Reservoirs	38
	Hydropower Systems	42
	Agricultural Water Use	45
	Municipal and Industrial Water Use	47
	Instream Recreation Water Use	49
	Reservoir Recreation Water Use	51
	Instream Flow Protection	52
	Conveyance Structures	54
	Other Water Uses Not Included in the Model	56

Chapter 4 **Benefit Functions** 57
Downward Sloping Price Benefit Functions 57
Variable-Head Powerplant 57
Fixed-Head Powerplant 61
Irrigation Demand Area 62
Municipal and Industrial Demand Area 64
Instream Recreation Area 65
Reservoir Recreation Activities 67
Constant Price Benefit Functions 69
Variable-Head Powerplant 69
Fixed-Head Powerplant 70
Irrigation Demand Area 70
Municipal and Industrial Demand Area 71
Instream Recreation Area 71

Chapter 5 **The Water Allocation Model** 73
Problem Statement 73
Objective Functional for Optimal Allocation 74
Solution Method 75
Objective Function Differentiation 78
Operational Restrictions 78
Modeling Uncontrolled Releases 83
Implicit Formulation of Reservoir Evaporation 83
Explicit Formulation of Reservoir Evaporation 85
Modeling Reservoir Spillages 87
Search for a Feasible Solution 89
Flow Cascading 90
Phase-1 of the Two-Phase Method 91
Time Intervals of Analysis 92

Chapter 6 **Symbolic Modeling of River Basin Systems** 95
Object-Oriented Programming Framework 95
Software Architecture 96
Top-Level Class Diagram 96
Class Categories 98
Mathematical Connectivity of System Components 105
Constraint Set Assemblage 107
Gradient Vector and Hessian Matrix Assemblage 110

Chapter 7 **How to Use AQUARIUS** 113
Systems Requirements 113
Exploring the Network Worksheet Screen 113
Network Worksheet (NWS) Screen 113
Menu Bar 114
Water System Components (WSC) Pallete 14
Tools Pallete 117
Creating a Flow Network 118

Entering Input Data 119
Physical Input Data 120
Economic Input Data 123
Updating Network Connectivity 124
Selecting the Optimization Technique 126
Specifying the Simulation Time Interval 127
Solving the Water Allocation Problem 128
Graphical and Tabular Output 129

Chapter 8 **Model Applications** 133
Description of the River Basin System 133
Defining Demand Functions 137
Finding an Efficient Water Allocation 138
Initial Feasible Solution 139
Final Solution 140
Changes in Offstream Water Demand 143
Change in Energy Price 145
Economic Efficiency for a Simple Case 146
Software Performance 147

Literature Cited 149

Appendix A **Derivatives of the Benefit Functions** 155
Derivatives of the Downward Sloping Benefit Functions 155
Variable-Head Hydropower Benefit Function 155
Fixed-Head Hydropower Benefit Function 158
Irrigation Benefit Function 159
Municipal and Industrial Benefit Function 160
Instream Water Recreation Benefit Function 160
Reservior Recreation Benefit Function 161
Derivatives of the Constant Price Benefit Functions 165
Variable-Head Hydropower Benefit Function 165
Fixed-Head Hydropower Benefit Function 167
Irrigation Benefit Function 168
Municipal and Industrial Benefit Function 168
Instream Water Recreation Benefit Function 168

Appendix B **Fitting Exponential Demand Functions** 169
Cases Considered 169
Basic Equations 169
Computing the Coefficients "*a*" and "*b*" 170
Fitting Example 172

Executive Summary

This report describes version 2000 (V00) of AQUARIUS, a state-of-the-art computer model devoted to the temporal and spatial allocation of water flows among competing traditional and nontraditional water uses in a river basin. The software runs on a personal computer under a Microsoft Windows 95, 98, NT or Windows 2000 operating system. Usage is free for government agencies and for teaching and research purposes. Consult one of the authors regarding private use.

Aquarius is an analysis framework rather than a single dedicated model for water allocation. Future versions of the model are planned. The model was implemented using an object-oriented programming (OOP) language (C++). Water systems are ideal candidates for modeling under an OOP framework, where each system component (e.g., reservoir, demand area, diversion point, river reach) is an object in the programming environment. Version 2000 supports the following water uses (system components):

- Storage reservoir
- Hydropower plants
- Agricultural water use
- Municipal and industrial water use
- Instream recreation water use
- Reservoir recreation water use
- Instream flow protection

An economic efficiency criterion was adopted for determining water allocation because economic demands play a key role in water allocation decisions, and because of the greater accessibility of economic value estimates for nontraditional water uses such as recreation. This decision criterion calls for reallocating stream flows until the marginal returns in all water uses are equal. Each traditional use and nontraditional use is, if possible, represented by a demand curve (i.e., a marginal benefit function) that is characterized by an exponential function.

For a water use with a predetermined level of allocation but without a defined economic demand function, 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.

The water allocation problem solved by Aquarius, involving a set of exponential/linear/ constant demand functions, requires a complex nonlinear objective function. The solution technique uses 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 approximates the original nonlinear objective function by a quadratic form using Taylor Series

expansion and solves the problem using quadratic programming. A succession of these approximations is performed using sequential quadratic programming until the solution of the quadratic problem reaches the optimal solution.

The user interacts with the model through the network worksheet screen (NWS), which represents the water system of interest using the inherent capability of the object-oriented paradigm for graphical representation. In the NWS, each water system component corresponds to an object—a graphical node or link—of the flow network. These components are represented by icons, which are pictorial representations of the objects. By dragging and dropping these icons from the menu, the model creates instances of the objects on the screen. Components can be repositioned anywhere in the NWS or can be removed. Once nodes (e.g., reservoirs, demand areas) are placed, they are linked by river reaches and conveyance structures. This operation occurs by left-clicking 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 connecting 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. Copy/paste creates new instances of the object(s) and duplicates their data structure, creating clones of the original objects.

The model's input data have been divided into physical and economic 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.

Although the present version of the model implements only a monthly time step, Aquarius was conceived to simulate the allocation of water using any time interval, including days, weeks, months, and time intervals of nonuniform lengths. 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 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.

Under the dominant water allocation doctrine in the Western United States—the Prior Appropriation Doctrine—the water available for a new application is reduced by the sum of all prior established rights. A priority-based allocation in a heavily appropriated river can become inefficient as values change if institutional barriers or market failures impede voluntary transfers of rights from lower-valued to higher-valued uses. Because institutional barriers and market

failures 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.

The latest distribution of the program Aquarius, together with it technical documentation, can be downloaded from the World Wide Web visiting the Aquarius web-page at: http://www.fs.fed.us/rm/value/aquariusdwnld.html. You may also visit the Colorado State University site at: http://www.engr.colostate.edu/depts/ce/research/aquarius/index.html

Chapter 1

Introduction

Water resource and environmental managers face increasing pressure to recognize traditional as well as nontraditional water uses. 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 of the geomorphological and biological integrity of a river, as well as providing opportunities for water-based recreational activities. To effectively integrate nontraditional water uses into a water management system, improved analytical tools are needed. This report describes such a tool. Aquarius is a river basin model that integrates traditional and nontraditional water uses using the most advanced computer programming language and graphics capabilities. This report is a comprehensive description of Aquarius including how to use it and examples of its use.

Modeling River Basin Systems

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 re-evaluated for license renewal. Such concerns require modeling to determine how water used for traditional activities and that used for nontraditional activities affect each other.

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 infancy of the environmental sciences has contributed to the diminished significance of nontraditional water uses in modeling efforts.

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 are generally not estimable in units commensurate with the traditional uses, so they are 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.

Also over the last three decades, 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. Used in the day-to-day operation of a water system, mathematical models provide guidance to operators who make real-time decisions concerning the quantity of water to be stored in or released from reservoirs, the amount of reservoir withdrawals, and offstream diversions. These decisions are all based on known or forecasted inflows and water demands in the basin.

Two basic categories of water resource models are simulation and optimization models. A simulation model is a conceptualization of a water system used to predict its hydrologic response and, in some cases, its economic performance under predefined operational conditions. Such models are based on water-balance accounting procedures for tracking the movement of water through a network of system components. Separate executions of a simulation model are generally needed to compare the response of a system under alternative system configurations, operating rules, demand levels, or natural flow sequences. The outputs from these multiple runs are evaluated by comparing the resulting time series of storage levels, reservoir releases, hydroelectric production, water supply shortages, water quality parameter values, etc. Some elements of optimization may be embedded within a reservoir system simulation model to perform certain specific tasks. Simulation models have typically been created from scratch to respond to the peculiarities of a given system, which precludes their reusability to model another water system. However, some general simulation models designed to be adapted to the conditions of a specific river basin are available, notably HEC-5, which was developed by the U.S. Army Corp of Engineers (1982).

Whereas simulation models are limited to predicting system performance for a user- specified set of decision rules or priorities, optimization models automatically search for an optimal solution to the water allocation problem. Optimization refers to a mathematical formulation in which a formal algorithm solves for values of a set of control variables that minimize or maximize an objective function, subject to pre-established operational restrictions. The objective function and constraints are represented by mathematical expressions as a function of the control variables.

In hydrologic optimization models, water inflows and demands are typically modeled deterministically; that is, they are known for all time periods of interest. The ability of an optimization model to base a decision (e.g., to allocate water) at any given time interval on foreknowledge of future inflows and water demands makes an optimization model distinct from a simulation model. However, an optimization model can be implemented one time period at a time, with the result used to determine the initial conditions for optimization of the next time period. When used this way, the optimization model performs somewhat like a simulation model.

Different types of objective functions may be used to measure system performance including utility and penalty functions or, preferably, mathematical expressions of a planning or operational objective. Several single objectives can be combined into a global objective function for the water system if all objectives can be expressed in commensurable units. When this is not possible, one of two approaches is usually adopted. The first approach is to use the primary objective as the objective function while treating the secondary objectives as constraints at fixed user-specified levels. The second approach is to construct a global objective function as a weighted sum of the different single objectives. Note that all optimization models have an embedded system simulation model on which the optimization acts. Because of the mathematical complexity involved in formulating optimization problems, general optimization models, designed to be easily adapted to the conditions of a specific river basin, have until now, been unavailable.

Elements of simulation and optimization models for water systems analysis are found in a third category of models, called network-flow models. Simulation models based on network-flow programming are a hybrid formulation that combines some advantageous features of simulation with some optimizing capability. Their simulation capability is limited to situations where specified quantities of water are to be stored or allocated to different users according to certain priorities expressed as weighing factors of a linear objective function. Variable priorities for a water use, such as those represented by a downward sloping demand function, can only be characterized in such models by stepping through a series of discrete levels that approximate the function. An important limitation of typical applications of the network-flow approach is that the optimal allocation of water is determined for each time interval of analysis independently rather than in a fully dynamic sense, as is typically required by multi-period problems in water resources.

Rogers and Fiering (1986) maintain that the most valuable role of systems analysis in water allocation is generating viable new alternatives to solve the water allocation problem. This is most effectively attained by using fully-dynamic optimization models. The series of alternatives, whose characteristics might be distinct, may form the basis of negotiation toward allocation of stream flows until the net marginal return in all water uses is equal. The key concept is "generation of new alternatives" rather than using the computer to track sequences of hydrologic input through the system, which only enforces already existing operation rules. When the analysis is carried out under the suggested framework, the techniques of systems analysis have the potential of significantly improving water resources planning and management.

Objectives

Our primary objective was to develop a water allocation model driven by an economic efficiency criterion that called for reallocating stream flows among traditional and nontraditional uses, subject to specified constraints, until the net marginal economic returns in all water uses was equal. We investigated economic and systems engineering techniques by which multipurpose river basin systems could be analyzed to reach an optimal allocation of flows. 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 available.

The modeling approach we adopted identifies tradeoffs between water uses by systematically examining, using a nonlinear optimization technique, the feasibility of reallocating water to alternative uses. The values of water in most uses are represented by economic value functions that express society's measured or estimated willingness to pay for different water uses. 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. The economic opportunity cost of allocating water to uses for which economic demand functions could not be estimated, such as the value of protecting an endangered fish species, would also be indicated.

For the purpose of planning and operation of multi-reservoir, multi-purpose water systems, we assessed the usefulness and adaptability of the following optimization techniques: Sequential Linear and Sequential Quadratic Programming, Dynamic Programming, Optimal Control Theory, and Extended Linear Quadratic Gaussian Control. We found that the optimization techniques most commonly used in reservoir-system optimization models are Linear Programming and Dynamic Programming, although nonlinear programming methods, including Optimal Control Theory, are also used. Although our modeling framework allows implementation of various solution algorithms, to date we have implemented only one algorithm category (sequential-approximation, a category within the realm of convex-programming) to solve nonlinear programming problems. Sequential-approximation algorithms, which include linear-approximation and quadratic-approximation methods, were selected because they can effectively handle the physical and economic nonlinearities found in real-world water resources allocation problems. Although sequential-approximation methods have been available for some time, because of their demand for computing time and memory, they have only recently become a practical option in personal computing.

Our secondary objective was to develop an easy to use model. A common problem of many river-basin models is that they are cumbersome to construct and amend. To improve this, we used the latest advances in programming languages to develop the software architecture and to provide graphical interfaces that simplify specifying the river basin components, entering the data, and interpreting the results.

Aquarius is 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 named after the ancient Greek personification Aquα̂rius, who, according to the Oxford University Press dictionary, was the "overseer of the public water supply" or the "superintendent for the supply of water." There were two previous versions of the software, version 96 and 99. The third and present version is 2000 (July 2000).

Among the large number of journal publications, books, and technical reports reviewed during this research, two classical references stand out: *Economics of Water Resources Planning* by James and Lee (1971), and *Water Resource Systems Planning and Analysis* by Loucks, Stedinger and Haith (1981). Both were important sources of inspiration.

Report Organization

The remainder of the report is organized as follows:

Chapter 2	presents the current water allocation systems in the United States and introduces the concept of water allocation under economic efficiency. This chapter also presents a complete overview of water demand functions for use in optimization modeling.
Chapter 3	introduces the operation and modeling assumptions adopted in the model for each of the water-using sectors possible in a basin.
Chapter 4	derives the economic benefit functions from all potential water users in a river basin and shows how are they quantified for the purpose of the model.
Chapter 5	presents the general approach to the solution of the water allocation problem as implemented in Aquarius. This chapter also provides the general mathematical formulation and details of the optimization technique.
Chapter 6	justifies the use of an object-oriented programming (OOP) framework for modeling water resources systems. This chapter also introduces the reader to some basic concepts of OOP and describes how they were used in the current modeling effort.
Chapter 7	familiarizes the reader with the use of the model by explaining the tools available for creating new flow networks, providing the necessary inputs, and finding and displaying optimal water allocations for the current problem.
Chapter 8	presents a hypothetical case study for a system of intermediate complexity. Besides describing the optimal system operation, it focuses on network subcomponents to further illustrate model capabilities.
Appendix A	introduces the mathematical derivations related to the adopted solution method.
Appendix B	presents the procedures for fitting exponential demand function based on user provided economic information.