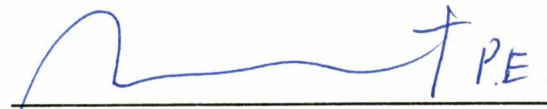
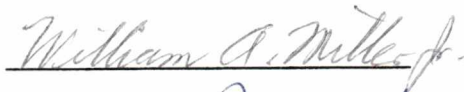


To the Graduate Council:

I am submitting herewith a thesis written by Patricia Suzanne Hardy entitled "An Evaluation of Rulebased Simulation as a Tool for Flood Risk Analysis: A Case Study on the Upper Holston System". I have examined the final copy of this thesis for form and content and recommend that it be accepted in partial fulfillment of the requirements for the degree of Master of Science, with a major in Environmental Engineering.


Bruce A. Tschantz, Major Professor

We have read this thesis
and recommend its acceptance:




Accepted for the Council:


Associate Vice Chancellor and
Dean of The Graduate School

**AN EVALUATION OF RULEBASED SIMULATION
AS A TOOL FOR FLOOD RISK ANALYSIS:
A Case Study on the Upper Holston System**

A Thesis
Presented for the
Master of Science
Degree
The University of Tennessee, Knoxville

Patricia Suzanne Hardy
December 1998

Dedication

I would like to dedicate this thesis to my parents
for all of their love and encouragement.

Acknowledgments

First, I would like to acknowledge my advisor, Dr. Bruce Tschantz,
for his ideas and direction throughout this long process.

I would also like to thank my other committee members,
Dr. James Smoot and Dr. William Miller.

Their comments and suggestions have greatly improved my work.

I would like to express my deep appreciation to
Morgan Goranflo and Richard Shane at TVA
for all of their guidance over the past three years.

I would like to thank Rusty Myers for his help and friendship.

Also, thanks to Arland Whitlock for having the foresight to save so many records,
which greatly helped in my literature review.

Most importantly, I would like to thank my husband and best friend,
Michael Patrick Biddle, for always being patient.

Abstract

RiverWare, a software package used in operating multipurpose reservoir systems, was developed by Tennessee Valley Authority, U. S. Bureau of Reclamation, and the Center for Advance Decision Support for Water and Environmental Systems (CADSWES) at the University of Colorado. Rulebased simulation, a modeling approach available in RiverWare is being developed as a tool in flood risk studies at TVA. Rulebased simulation allows the user to characterize reservoir system operating policies in the form of prioritized rules. Flood risk assessments will be facilitated because a consistent set of operating constraints can be applied to a reservoir system while inflow forecasts are varied. This allows reservoir operators to quickly and easily realize the uncertainty associated with weather and inflow forecasting. This thesis discusses rulebased simulation as it is applied to the Upper Holston watershed, a subbasin of the Tennessee River watershed.

Three actual storm events in the Upper Holston watershed were modeled using rulebased simulation. An exact replication of actual operations was not achieved and was not expected because of the many changes in operating policies and modeling capabilities that have occurred over the years. However, these storms were used to test rulebased simulation during the development phase as well as make a qualitative assessment regarding the applicability of RiverWare rulebased simulation in a flood risk study. The ability to easily write and modify rules to reflect changes in operating policy makes it a valuable asset to flood risk investigators and reservoir operators.

In conclusion, RiverWare rulebased simulation is a tool that should be used to facilitate the decision making process of reservoir operators regarding current and future operations of the TVA reservoir system.

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Glossary

Reservoir Operations Nomenclature:

Daily Operating Zone - Range of headwater elevations in which some tributary reservoirs are allowed to fluctuate during normal daily operations. Reservoirs that have a daily operating range are generally utilized for power production and do not have substantial flood storage space. The headwater elevation at a reservoir typically does not drop below the minimum elevation of this range, known as "bottom of daily operating zone", under normal operating conditions. Also, the headwater elevation at a reservoir typically does not exceed the maximum elevation of this range, known as "top of daily operating zone".

Flood Guide - Elevation guide curve for tributary reservoirs, established when the reservoirs were constructed, that maintains flood storage availability, particularly during the winter, spring, and summer seasons. These elevations were determined for each reservoir based on runoff and required storage space to protect downstream areas from flooding.

Guide Curve - A graphical representation of headwater elevation versus time of year. Reservoirs are operated so that headwater elevations will correspond as closely as possible to their respective guide curves throughout the year. Some guide curves were established when dams were constructed. Others were added over the years. Guide curves reflect seasonal hydrologic variations throughout the year. For instance, most floods in the Tennessee Valley occur during the late winter and early spring. Therefore, guide curves are generally lower during this time of year reflecting the need for increased runoff storage space in reservoirs. Guide curves are generally higher during the summer months when runoff is lower and recreational benefits are a priority. Examples of guide curves are minimum operation guides and flood guides.

Minimum Operation Guide (MOG) - Minimum elevation guide curve for tributary, storage reservoirs that is maintainable during 9 of 10 years. If the headwater elevation at a particular dam drops below this elevation, discharge from this dam should not exceed minimum flow requirements.

Tributary Reservoir - A reservoir that is located on a tributary to the Tennessee River.

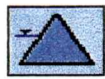
Top of Gates (TOG) - Elevation of the top of the spillway gates at a dam.

RiverWare Nomenclature:

Graphical User Interface (GUI) - A windows based tool that allows user interaction with an application.

Object - Real world entities represented electronically by pieces of modeling code.

Objects:



Storage Reservoir - Represents a level pool reservoir with no hydropower.



Level Power Reservoir - Represents a level pool reservoir with hydropower.



Slope Power Reservoir - Represents a reservoir with slope storage and hydropower.



Pumped Storage Reservoir - Represents a level power reservoir with inflow pumped from another reservoir.



Stream Reach - Used for river reach routing.



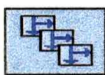
Aggregate Reach - Multiple reaches represented by one object.



Confluence - Combines two inflows to obtain one outflow as in a stream confluence.



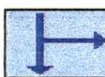
Canal - Represents bidirectional flow between two reservoirs.



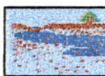
Aggregate Diversion Site - Multiple diversions represented by one object.



Aggregate Distribution Canal - Generates demands and models supplies to off-line water users.



Diversion - Diversion structure with gravity or pumped diversion.



Groundwater Storage - Stores water from return flow.



Stream Gage - Allows user input of required minimum flow.



Thermal Object - Represents power economics.



Data Object - Can be customized by the user to include equations or other information used in modeling a reservoir system.

RiverWare - Object-oriented software written in C++ used in modeling multipurpose reservoir systems.

Rule - A policy statement written in “if-then” format.

Rulebased Simulation - The controller methodology within RiverWare “that directs the simulation of a river and power system network based on user-specified operating policies or rules” (Wehrend, 1997).

Ruleset - A set of rules which direct simulation of a river network within RiverWare.

I. Literature Review

A Brief History of Computer Modeling within TVA River System Operations

Computer applications for inflow forecasting and reservoir scheduling began at TVA in the 1950's. Prior to this time, all data collection was done via phone lines, utilizing human observers, and all computations were done manually. Inflows were forecast manually using unit hydrographs for up to six days into the future and reservoir releases were computed manually based on these inflow forecasts. Data was written and plotted by hand, and only hard copy storage was available. Beginning in 1957, a computer was used to calculate rainfall averages, predict runoff, and forecast resulting streamflow. The six day forecast period was still used but was extended to ten days in the early 1960's. To complete this process, three different computer runs were required, making use of punch tapes.

In about 1960, the first computerized backwater profiles were generated for reservoirs on the Tennessee River. During the 1960's, a transition was made to punch cards which had to be transported to a computer located in Chattanooga, Tennessee. Although many computations were still made by hand, another advancement was made which allowed the input of rainfall observations and the output of predicted streamflow, without having to complete three model runs.

In the early 1970's, the first "real-time" reservoir scheduling model was written for Kentucky and Barkley reservoirs, which are located on the lower Tennessee River and the lower Cumberland River, respectively. At about the same time, a transition was made to "time sharing computers" on which TVA rented run time. This allowed "run

control, data input, and printout of results at a terminal within River Management Branch offices" (Courtney, 1978) now called River System Operations. In 1974, the Dial Interrogation Hydrologic Gaging System (DIHGS) "began preliminary tests of automated rainfall and streamflow reports" (Courtney, 1978). Initially, a total of 25 gages were automated, including 15 rain gages and 10 stream gages. An additional 100 rain gages and 50 stream gages were added during the late 1970's. It was late in the 1980's before all rain and stream gages in the Tennessee Valley were automated.

Until the late 1970's, "most data was received manually through telephone reports, by telecopier, and by teletype" (Courtney, 1978). This data was "recorded on standard forms, streamgage readings converted to flows, and plotting of pertinent data completed manually. Rainfall data is manually entered into the computer for processing programs to provide flow forecasts. Observed operations for the previous data are analyzed through manual computations and inspections and plotting of results. Operations planning activities are carried out with manual computations based on visually adjusted flow forecasts and verbal communications. System operations plans are provided through telephone, teletype, telecopier, and mail communications" (Courtney, 1978).

TVA reservoir operations personnel realized during the 1970's that increasing demands being placed on the reservoir system, such as recreation and water supply, would increase the complexity of operations. Also hydro optimization was being considered. Additionally, there was a large increase in the demand for computer services both within and outside of TVA, and concerns were mounting about computer system

reliability and availability of a backup in the event of hardware failure. Therefore, a project to enhance computer operations as well as procure a computer system for use in house was undertaken. The result was development and implementation of WATREMAIN, Water Resources Management Information System, during the 1980's.

"The WATREMAIN project was the first comprehensive effort to analyze and document the data management need, the procedures, and the program development to support a full range of TVA reservoir operations activities" (Courtney, 1988).

WATREMAIN was composed of four subsystems: data collection, data analysis, operations planning, and data exchange and publication. "Implementation of the WATREMAIN concept has been successful primarily because the computer applications and procedures were designed to complement rather than to replace the decision-making by reservoir operations engineers. The interrelated programs and procedures were specifically designed to eliminate the drudgery of manual data collection and processing as well as the manual arithmetic calculations that were so susceptible to errors. Time-consuming table lookups and checks for accuracy of computations are no longer required, giving engineers more time to examine alternative operations and to better respond to rapidly changing flow conditions" (Courtney, 1988).

WATREMAIN was very successful, but advances in technology allowed for an even greater integration of computers into reservoir operations. During the late 1980's, TVA initiated the ROBECS (Reservoir Operations Branch Enhanced Computer System) project. Some of the goals of ROBECS were to: 1) improve rainfall-runoff modeling, 2)

improve water quality modeling, and 3) develop long-range planning models for the Tennessee River basin.

As part of the ROBECS project, an interactive inflow model was developed which has been enhanced over the years and is still used today. This interactive inflow model graphically displays observed and predicted hydrographs for each subbasin. The user has the option to adjust hydrologic factors influencing predicted hydrographs. Also as part of ROBECS, reservoir routing models were developed which performed mass balance computations. However, power computations were still performed by hand. A weekly scheduling model was developed which executed on weekly timesteps in order to be used in long range planning studies. Eventually, power computations were added to the reservoir scheduling models. The entire Tennessee system was segmented into several different models. Consequently, models for each of the tributary subsystems had to be analyzed in order to provide inputs into the scheduling model for the Tennessee River. By the late 1980's, all data collection was automated, reservoir modeling was computerized, and statistical computations such as rainfall and runoff averages were performed via computer.

Further advances in computers, including windows technology, were the impetus for upgrading computer systems once again in the late 1980's and early 1990's. The current system used in operating the Tennessee Valley reservoir system consists of several work stations networked to a file server which runs on the UNIX operating system. Software development has continued and the latest modeling environment used in TVA River System Operations is RiverWare. This software has many advantages

over previous models. RiverWare was not written for a specific river basin. Instead, it is a generic software tool that can be used to model any river basin. This allows an entire reservoir system to be modeled as a whole or segmentation of a large river system into smaller subsystems. Also, not only does RiverWare perform mass balance calculations within a simulation mode, it also features rulebased simulation and optimization. Additionally, timesteps within a model run and length of model run can be changed by the user, which allows RiverWare to be used in a wide number of modeling capacities. For instance, RiverWare can be used for daily scheduling of a reservoir system or can be used in long-term planning studies for years into the future. For a more detailed discussion of RiverWare, particularly rulebased simulation which is the subject of this thesis, refer to Section V.

Other “Rule” Software and Decision Support Software Used in Reservoir Operations

Computer software used in water resource management is constantly improving, making the operation of a reservoir system much more efficient. This improved efficiency allows reservoir operators to evaluate a wide range of possible operating scenarios which would have been prohibitively time consuming in the past. For example, the entire TVA reservoir system can be represented in one RiverWare model. By using the RiverWare software in this capacity, the operator can quickly determine how a change in discharges from an upstream tributary reservoir will impact the entire system. By simply inputting a proposed operating scenario and running the model, the

user can, within a matter of moments, realize the implications of this input. If the desired results are not achieved, the user can quickly and easily test another scenario. Computer software currently available to aid in the operation of a reservoir system includes simulation, rulebased, and optimization models, as well as decision support systems.

There are several references in literature to rule based types of models, many of which incorporate fuzzy logic. Rulebased models that incorporate fuzzy logic often use an "if-then" structure. Niimura and Yokoyama (1995) describe an "if-then" structure in their paper entitled "Water Level Control of Small-scale Hydro-Generating Units by Fuzzy Logic". They point out that if-then logic is very similar to the way in which humans reason. Therefore, it is quite easy for engineers to formulate if-then rules. However, many of the objectives of operating a reservoir system conflict, so it is often difficult for humans to find a compromise. An example of two operating objectives that often conflict is maintaining flood storage availability while attempting to provide pool elevations that are optimal for recreation. Fuzzy rulesets help perform the decision making for the operator once the rules are configured.

Another example of reservoir modeling using a fuzzy rulebased model is described by Shrestha, et. al (1996). In their paper, "Fuzzy Rule-Based Modeling of Reservoir Operation", they describe a ruleset also using if-then logic. They point out that the vagueness associated with reservoir operations can be dealt with using fuzzy logic. This vagueness refers to the uncertainty of inflows and evaporation and seepage losses which influences pool levels as well as the uncertainty of other demands placed on the system, such as power loads, and "the operator's subjective judgment during the release

operation” (Shrestha, 1996). This vagueness is accounted for by using probability for the premise or “if” values. The authors point out that a “system expert” must be available to define rules and interpret results. They also use observed events as training or calibration sets for defining fuzzy logic.

Another type of software available to reservoir operators that could be beneficial in making decisions regarding flood risk is decision support systems (DSS). “Decision support systems are interactive computer based systems which help decision makers utilize data and models to identify and solve problems and make decisions. DSS help managers/decision makers use and manipulate data; apply checklists and heuristics; and build and use mathematical models. A DSS has four major characteristics: 1) DSS incorporate both data and models; 2) they are designed to assist managers in their decision processes in semistructured (or unstructured) tasks; 3) they support, rather than replace, managerial judgment; and 4) their objective is to improve the effectiveness of the decisions” (<http://dss.cba.uni.edu/glossary/dssglossary.html>). Many of the objectives in reservoir operations are conflicting and the decisions made regarding these operations are often subject to the judgment of the responsible operator. Decision support systems can formalize an otherwise unstructured decision making process.

There are many types of software available to the engineer to facilitate the often difficult decision making process and, therefore, enhance the operation of a reservoir system. Examples include rulebased software such as RiverWare rulebased simulation and other commercially available software packages utilizing fuzzy logic. Additionally, decision support systems can incorporate modeling software with other software to aid in

decision making during day-to-day operations as well as long-term policy planning and precedents for future practices (Reitsma, 1996).

II. Introduction

The Tennessee Valley Authority (TVA) was formed in 1933 by the TVA Act (U.S. Statutes at Large, 1933). Since then, TVA has acquired or built 54 dams, which are operated primarily for the purposes of promoting navigation, controlling floods, and “so far as to be consistent with such purposes” generating electricity (U.S. Statutes at Large, 1935). Throughout the history of TVA, reducing the risk of flooding in the Tennessee Valley has been a top priority in operating the reservoir system. While this still holds true, the prospect of deregulation of the utility industry has increased the importance of flexible hydropower. Therefore, more demand has been placed on operators of the reservoir system to use hydropower to its maximum value while still meeting other operational constraints on the system.

Oftentimes, operations that produce maximum hydropower value are not consistent with meeting other operational objectives for the system such as flood control, navigation, and recreation. For example, maintaining adequate flood storage space often means spilling water which, if saved, could be used later for power generation. During high flow periods, storage space is often utilized in reservoirs to protect downstream areas from flooding. Following high flow events, flood storage space is usually regained as quickly as possible. Economic benefits could be derived by holding this water in storage as long as possible rather than spilling it. However, by not regaining flood storage space quickly following a high flow event the risk of future flooding could be increased.

The risk of not having flood storage available, if needed, has been somewhat mitigated over the years by improvements in weather forecasting. However, the ability to forecast rainfall and resulting runoff amounts is still limited, necessitating the evaluation of the full range of flood damage possibilities when flood storage is temporarily utilized. By using different "predicted rain" weather forecasts, an array of reservoir operating schedules can be generated which allows operators to be prepared for a number of potential circumstances. By utilizing predicted rain, reservoir operators are able to make decisions based on foresight that would not have been possible years ago. If a rainfall event is predicted for some time within the forecast period, operators would likely try to regain flood storage space much more quickly following a storm than if a dry period is anticipated. Uncertainties associated with flood storage space availability, weather forecasts, power generation, and many other constraints must all be weighed in scheduling the hydro system, with economics playing an ever increasing role.

One tool being developed for use in the analysis of future flood risk is rulebased simulation, which is part of a modeling framework known as RiverWare. Rulebased simulation within RiverWare allows the user to express reservoir operating policies in the form of prioritized rules. These rules are executed within a simulation model run. The rules currently being used by TVA in rulebased simulation express the operational guidelines of each reservoir represented in the model. These operational guidelines depict the desired elevation ranges at each reservoir throughout the year. By using rulebased simulation, many different modeling scenarios can be investigated. Each scenario could have different initial conditions and inflow values, but the operational

guidelines of the reservoir system remain constant. With the use of forecasted inflows, an analysis can be made to determine whether or not holding reservoir elevations higher after a flood event will significantly increase the risk of future flooding.

III. Objective

The objective of this thesis is to evaluate the applicability of RiverWare rulebased simulation as a tool in a flood risk analysis study. This evaluation will be based more on a qualitative assessment of RiverWare rulebased simulation than a quantitative analysis of modeling results. The initial application of rulebased simulation will concentrate on one specific basin within the Tennessee Valley. This basin is the Upper Holston watershed which includes five reservoirs: South Holston, Watauga, Wilbur, Boone, and Fort Patrick Henry. This watershed is significant because of the flooding concerns in Elizabethton, Tennessee, downstream of Wilbur dam and Kingsport, Tennessee, just downstream of Fort Patrick Henry dam. Questions to be answered include: Can rules be written that drive a model to operate a reservoir system in a manner reflective of actual operations? Is this tool easily adaptable to changes in operating policy? Does rulebased simulation help reservoir operators make decisions that could impact current and future operations?

In order to apply a rulebased model to the Upper Holston system, the operating guidelines of the system have to be defined. Although there are some procedures established for reservoir operations in the Upper Holston system, more often, operating decisions are based on experience rather than a defined policy. Also, operating decisions made at any one time not only take into consideration conditions within the Upper Holston system, but also the impacts that the operations will have on other areas of the Tennessee Valley, such as Chattanooga, Tennessee. This makes defining a realistic operating policy that can be written in the form of prioritized rules extremely difficult.

After a set of operating guidelines for the Upper Holston system are written which as closely as possible resemble actual operating objectives, they will be modeled using RiverWare rulebased simulation.

A comparison of results from rulebased simulation model runs with actual operations of the Upper Holston system during three different high flow events will be presented. Observed inflows are used as inputs into the model runs, as well as all other physical constraints such as unit outages. Although a comparison will be made between modeled results and actual operations, the reader should not expect an exact replication of observed data. The objective is not to replicate actual operations, but to study the application of this modeling tool to one subsystem of the Tennessee River and make a determination as to whether it should be expanded to include the entire Tennessee River reservoir system.

Primary reasons that actual operations of reservoirs in the Upper Holston system will not be exactly duplicated are: 1) operating policies have changed over the years. The ruleset used for this study reflects current operating guidelines which may differ from those of the past., 2) the ruleset used in this study has been written to reflect operating constraints on the Upper Holston system, without regard for impacts to the remainder of the Tennessee Valley. The entire Tennessee system is not modeled, and therefore, the impacts of the operation of the Upper Holston system cannot be determined., and 3) the hydrologic inflows into each reservoir are those which actually occurred, which means that perfect foresight is available. This sharply contrasts the conditions under which reservoir operators typically work, where they did not have the

luxury of knowing the exact amount of rainfall and resulting runoff that will occur.

Therefore, operating decisions have to be made based on observed rainfall amounts and precipitation predictions which may not always be accurate forecasts. However, a conclusion can still be drawn that answers the question "Can rules be written that drive a model to operate a reservoir system in a manner reflective of actual operations?".

From a developer's perspective the question "Is this tool easily adaptable to changes in operating policy?" will be answered. Also, from a user's perspective the question "Does rulebased simulation help reservoir operators make decisions that could impact current and future operations?" will be answered. This is particularly important because guidelines for reservoir operations are continually changing to reflect the evolving constraints placed in the system as well as improvement in forecasting ability. If a determination is made that this tool is beneficial in a flood risk study, the model will be expanded to include all of the reservoirs in the Tennessee Valley.

IV. Description of the System Being Modeled

The reservoirs in the Tennessee Valley are operated to control flooding at several pertinent locations including Chattanooga, the primary damage center, as well as Kingsport and Elizabethton, Tennessee, which are located within the Upper Holston watershed (Figure 1). This watershed, located in northeast Tennessee, is comprised of five reservoirs: South Holston, Watauga, Wilbur, Boone, and Fort Patrick Henry (Figure 2). The total drainage area is 1903 square miles (TVA, 1980). "The basin is roughly triangular in shape... The eastern edge lies in the Blue Ridge Mountains where it forms the eastern border of the Tennessee Valley. The greater portion of the watershed above the Watauga and South Holston projects is composed of rugged, mountainous terrain generally covered with second growth timber. Agricultural lands in this area are very limited and are confined to small narrow valleys. Downstream near the junction of the Watauga and South Fork Holston Rivers, the terrain becomes much less rugged with rolling hills and flat valleys" (TVA, 1958). Rainfall in the Upper Holston watershed averages about 45 inches per year with runoff averaging about 18.5 inches per year (TVA Water Management Files, 1998).

Kingsport is located 2.5 miles downstream of Fort Patrick Henry dam and Elizabethton is located 10.5 miles downstream of Watauga dam. Discharges above 11,500 cubic feet per second (cfs) have the potential to cause flooding in Kingsport, particularly at Eastman Chemical Company. Elizabethton is vulnerable to potential flood damages at discharges of more than 5,000 cfs (Goranflo, personal communication, December 2, 1997).

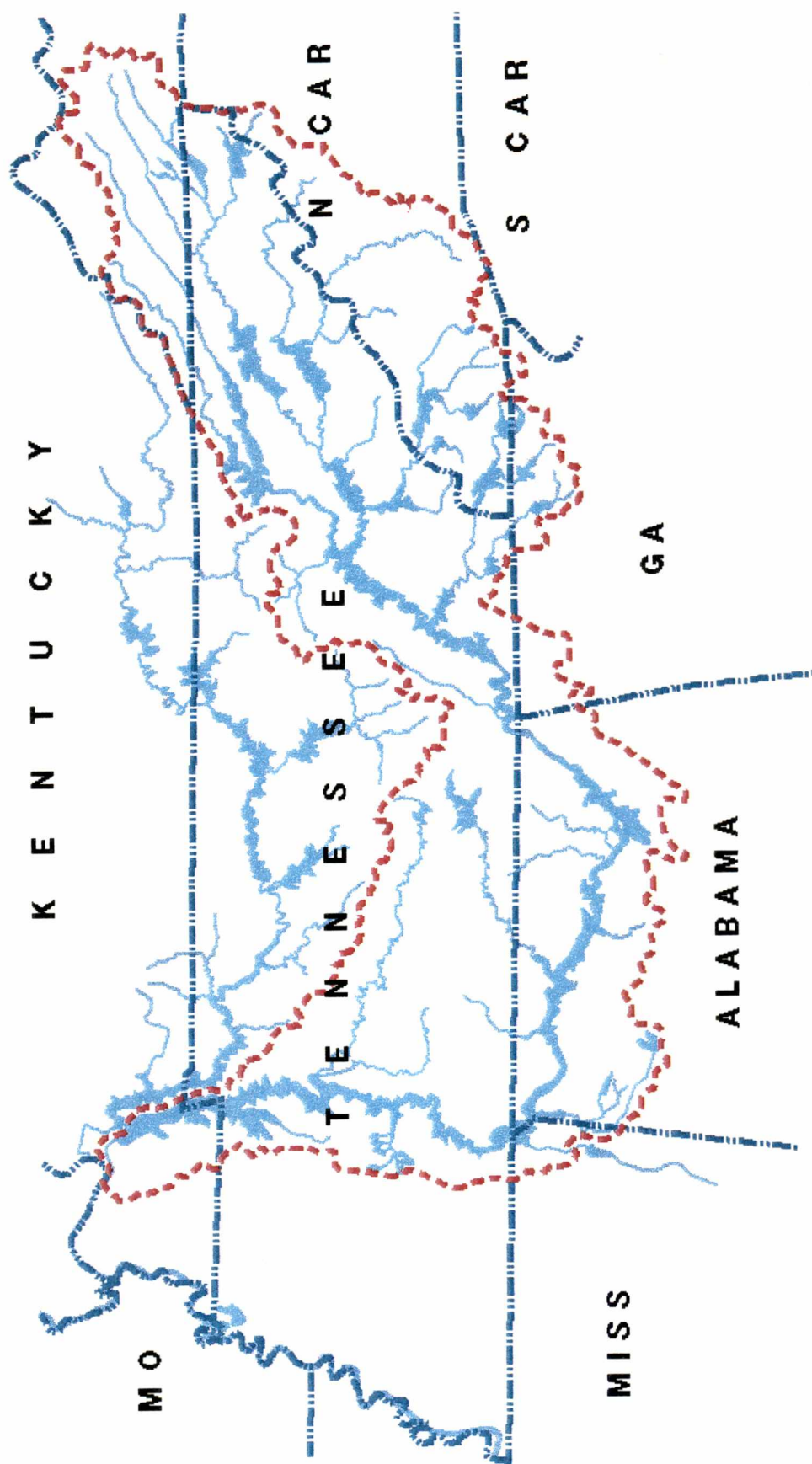


Figure 1. Map of the Tennessee River Watershed.

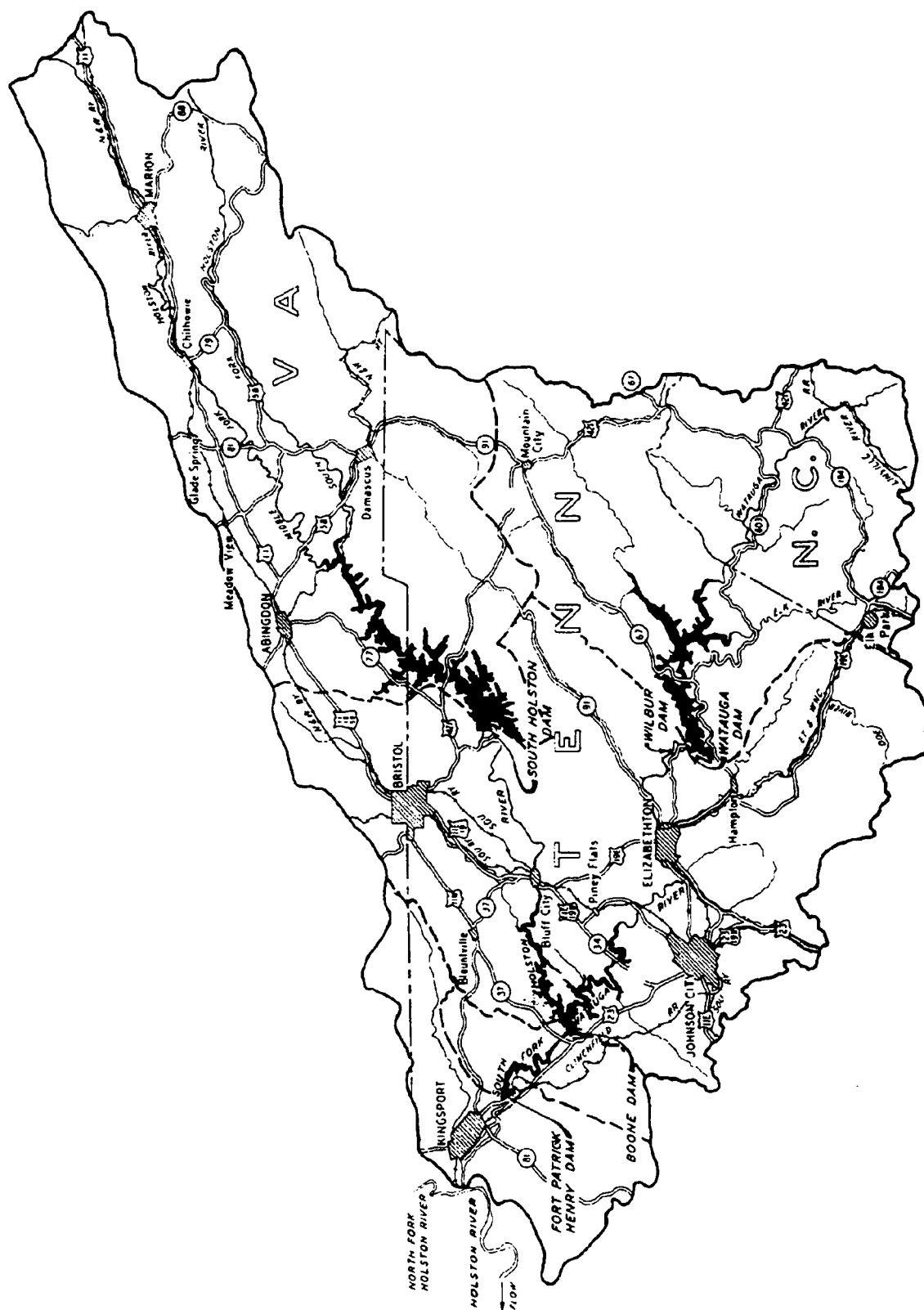


Figure 2. Map of the South Fork Holston River Drainage Basin Showing Upper Holston Project Locations.

South Holston Reservoir

South Holston dam, located on the South Fork Holston River, has a drainage area of 703 square miles. The reservoir lies in parts of Sullivan County Tennessee and Washington County Virginia. The storage volume at the top of the normal summer pool (1729 feet above msl) is 657,500 acre-feet (See elevation-volume curve in appendix). Turbine capacity is about 3,300 cfs. In addition to one turbine, there is a morning glory spillway (crest elevation 1742 feet above msl) with a discharge capacity of 62,000 cfs, a sluiceway with a discharge capacity of 11,000 cfs, and an uncontrolled overflow weir (crest elevation 1744 feet above msl) with a discharge capacity of 43,000 cfs. Discharges from South Holston dam travel down the South Fork Holston River before flowing into Boone reservoir. The average travel time of discharge from South Holston dam to Boone dam is approximately eight hours.

Watauga Reservoir

Watauga dam, located on the Watauga River, has a drainage area of 468 square miles. The reservoir lies in parts of Carter and Johnson Counties in Tennessee. The storage volume at the top of the normal summer pool (1959 feet above msl) is 568,700 acre-feet (See elevation-volume curve in appendix). Turbine capacity is about 3,300 cfs. In addition to two turbines, there is a morning glory spillway (crest elevation 1975 feet above msl) with a discharge capacity of 62,000 cfs and a sluiceway with a discharge capacity of 11,500 cfs. Discharges from Watauga dam flow directly into Wilbur reservoir.

Wilbur Reservoir

Wilbur dam is located on the Watauga River 2.7 miles below Watauga dam with an uncontrolled drainage area of 3 square miles. The reservoir lies in Carter County Tennessee. Wilbur is operated within a 5 foot elevation range throughout the year, primarily for the generation of hydropower. There is very little flood storage availability in the reservoir (See elevation-volume curve in appendix). Turbine capacity is about 3,000 cfs. In addition to four turbines, there is a regulated spillway (crest elevation 1635 feet above msl) with a discharge capacity of 34,000 cfs. Wilbur was purchased by TVA from East Tennessee Light & Power Co. in June 1945. Discharges from Wilbur dam travel down the Watauga River for approximately eight hours before flowing into Boone reservoir which forms at the confluence of the South Fork Holston River and the Watauga River.

Boone Reservoir

Boone dam, located on the South Fork Holston River 1.4 miles below its confluence with the Watauga River, has an uncontrolled drainage area of 666 square miles. The reservoir lies in parts of Sullivan and Washington Counties in Tennessee. The storage volume at the top of the normal summer pool (1383 feet above msl) is 184,800 acre-feet (See elevation-volume curve in appendix). Turbine capacity is about 11,000 cfs. In addition to three turbines, there is a regulated spillway (crest elevation 1350 feet above msl) with a discharge capacity of 137,000 cfs and a sluiceway with a

discharge capacity of 3,800 cfs. Discharges from Boone dam flow directly into Fort Patrick Henry reservoir.

Fort Patrick Henry Reservoir

Fort Patrick Henry dam is located on the South Fork Holston River 10.4 miles downstream of Boone dam with an uncontrolled drainage area of 63 square miles. The reservoir lies in parts of Sullivan and Washington Counties in Tennessee. Fort Patrick Henry is operated within a 5 foot elevation range throughout the year primarily for the generation of hydropower. There is very little flood storage availability in the reservoir (See elevation-volume curve in appendix). Turbine capacity is about 8,000 cfs. In addition to turbine releases, there is a regulated spillway (crest elevation 1228 feet above msl) with a discharge capacity of 141,000 cfs.

Table 1 summarizes selected characteristics of each of the reservoirs in the Upper Holston system. Figure 3 shows a profile of the Upper Holston projects.

Table 1. Selected Characteristics of Reservoirs in the Upper Holston System.

RESERVOIR	ELEVATION AT FULL POOL (FEET)	STORAGE AT FULL POOL (ACRE-FEET)	UNCONTROLLED /TOTAL DRAINAGE AREA (SQUARE MILES)	TURBINE CAPACITY (CFS)	TYPES OF SPILLWAYS	SPILLWAY CAPACITIES (CFS)
South Holston	1729	657,500	703/703	3,300	morning glory sluice weir	62,000 11,000 43,000
Watauga	1959	568,700	468/468	3,300	morning glory sluice	62,000 11,500
Wilbur	1648.5	595	3/471	3,000	regulated	34,000
Boone	1383	184,800	666/1840	11,000	regulated sluice	137,000 3,800
Fort Patrick Henry	1263	26,900	63/1903	8,000	regulated	141,000

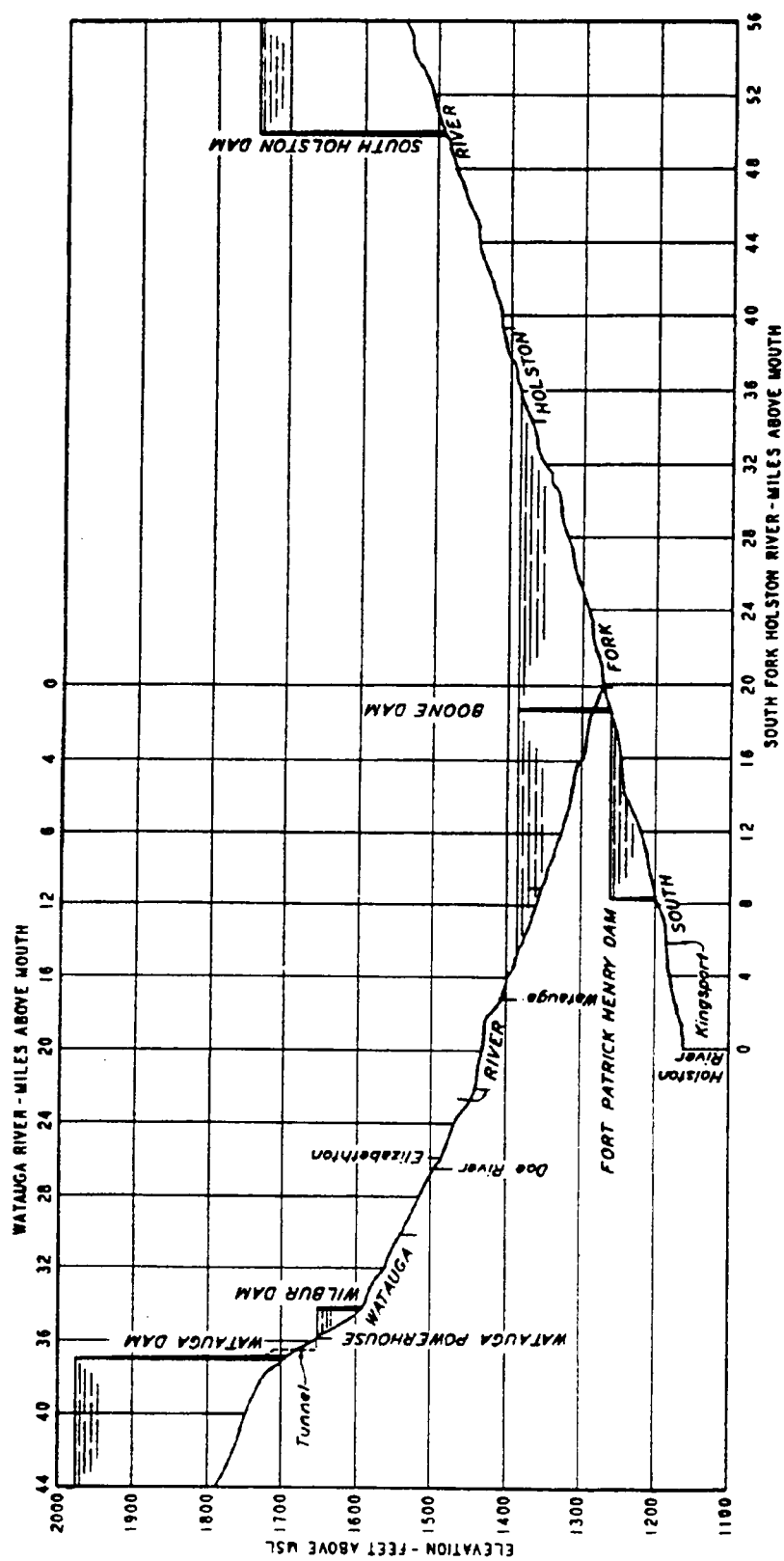


Figure 3. Profiles of the Upper Holston Projects.

Operating Guidelines

An Environmental Impact Statement (EIS) published by TVA in December 1990 established operating guidelines for each of the major tributary storage projects in the Tennessee Valley. Minimum operation guides (MOGs), minimum flow requirements, and summer lake levels were established as a result of the EIS, Tennessee River and Reservoir System Operation and Planning Review (1990). This EIS, commonly referred to as the Lake Improvement Plan, established minimum operation guides that could be maintained during 90 percent of the years at the tributary storage projects. In the Upper Holston system, two reservoirs, South Holston and Watauga, have minimum operation guides (Figures 4 and 5).

In addition to minimum operation guides, South Holston and Watauga also have flood guides, which were established when the projects were constructed during the 1940's (TVA, 1958). Elevation guides 1, 2, and 3 were established later as guidelines for operating the two reservoirs when elevations exceed flood guide levels but are below top of gates elevations (Figures 4 and 5). Elevation guides 1, 2, and 3 are not official TVA policy, but are considered "rules of thumb", in that actual operations may vary depending on conditions in the reservoirs, downstream conditions, and weather forecasts. Each elevation guide is associated with a discharge guide. These elevation and discharge guides represent typical operations of the reservoirs to maintain flood storage space.

The remaining three reservoirs in the Upper Holston system are not considered major storage reservoirs and are operated differently from South Holston and Watauga. Although Boone does have some flood storage space available, it is relatively small

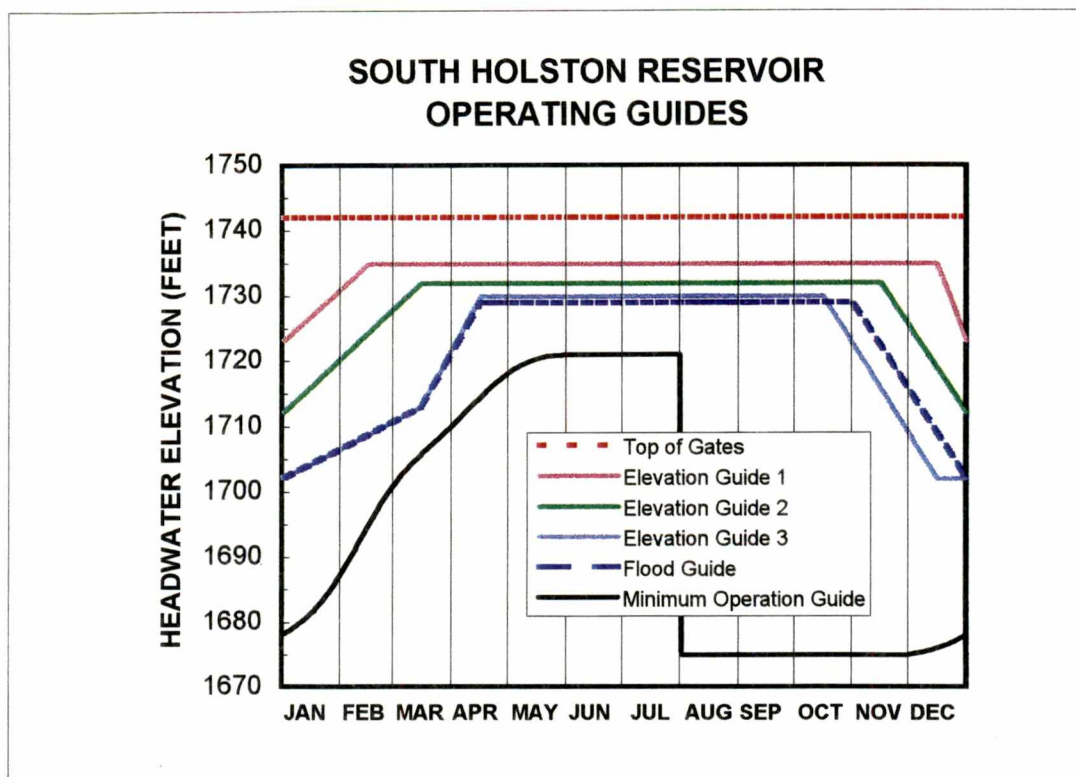


Figure 4. South Holston Reservoir Operating Guides.

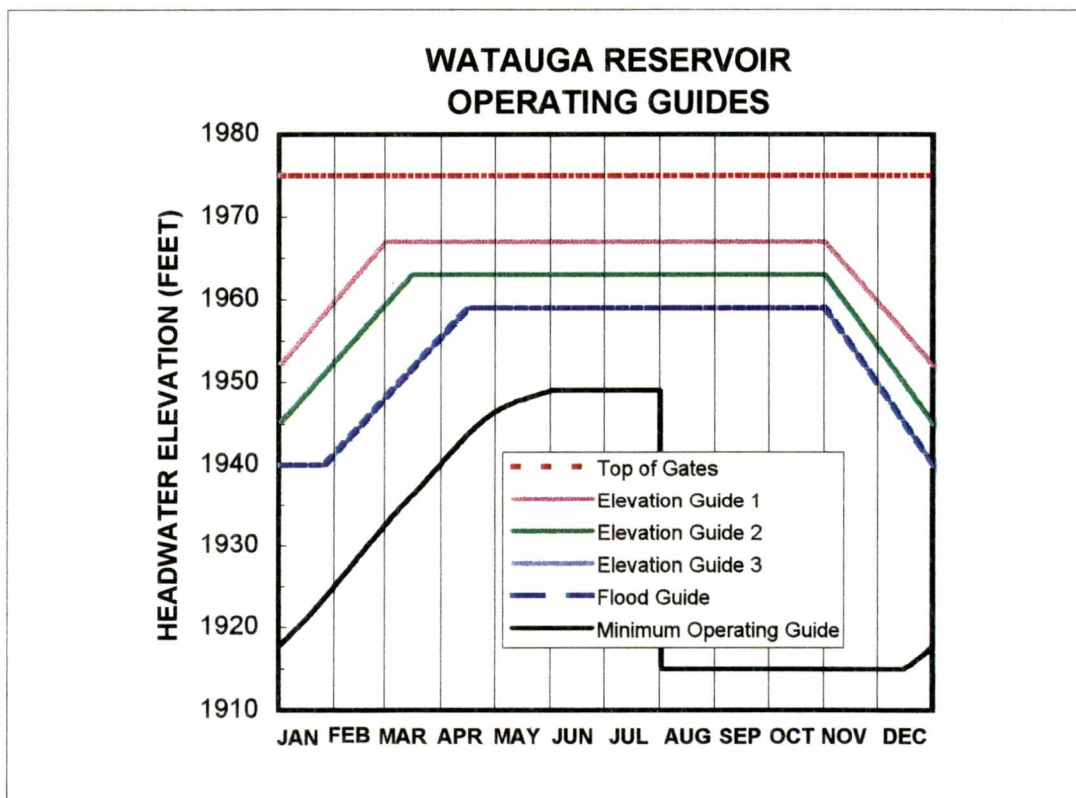


Figure 5. Watauga Reservoir Operating Guides.

compared to the two upstream reservoirs. Boone reservoir has an elevation guide 1 along with a top of daily operating zone guide and a bottom of daily operating zone guide. Within this zone of daily operation is a balancing guide which represents optimal conditions (Figure 6). Boone also has a surcharge elevation which would only be utilized in extreme circumstances to protect the downstream damage center of Kingsport, Tennessee. The remaining two projects, Wilbur and Fort Patrick Henry, have very little storage space and are operated within a narrow elevation range through the year (Figures 7 and 8).

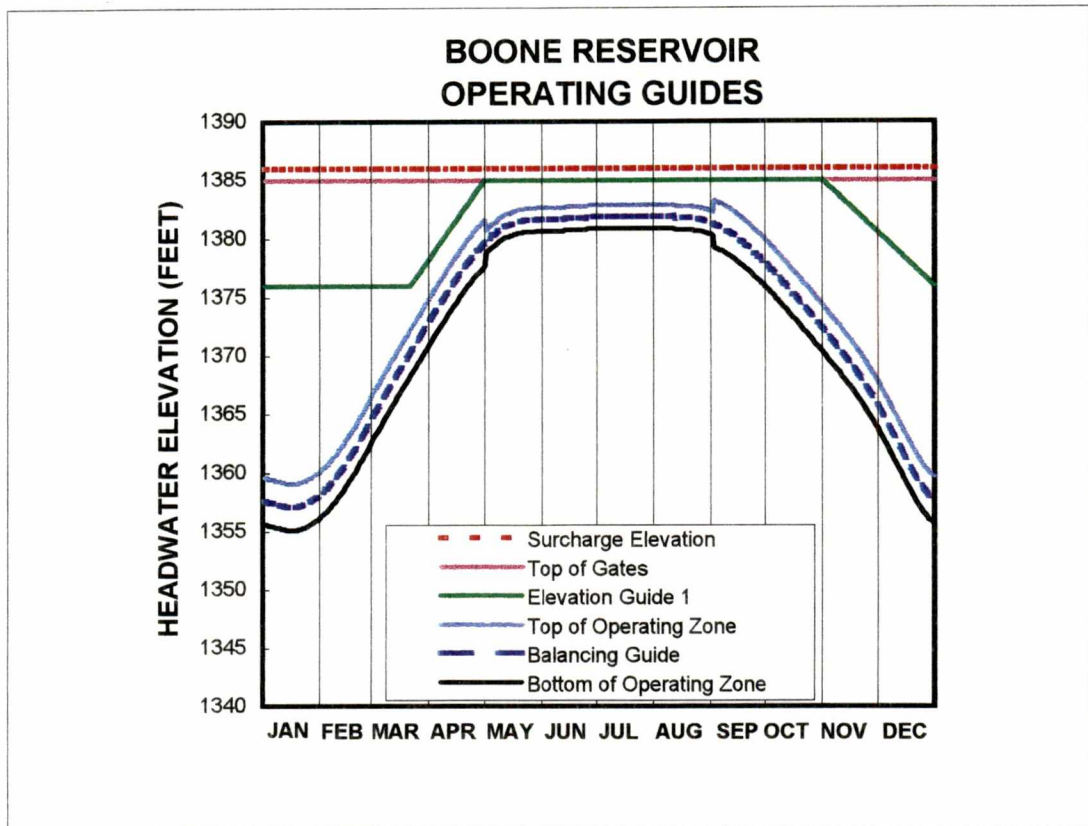


Figure 6. Boone Reservoir Operating Guides.

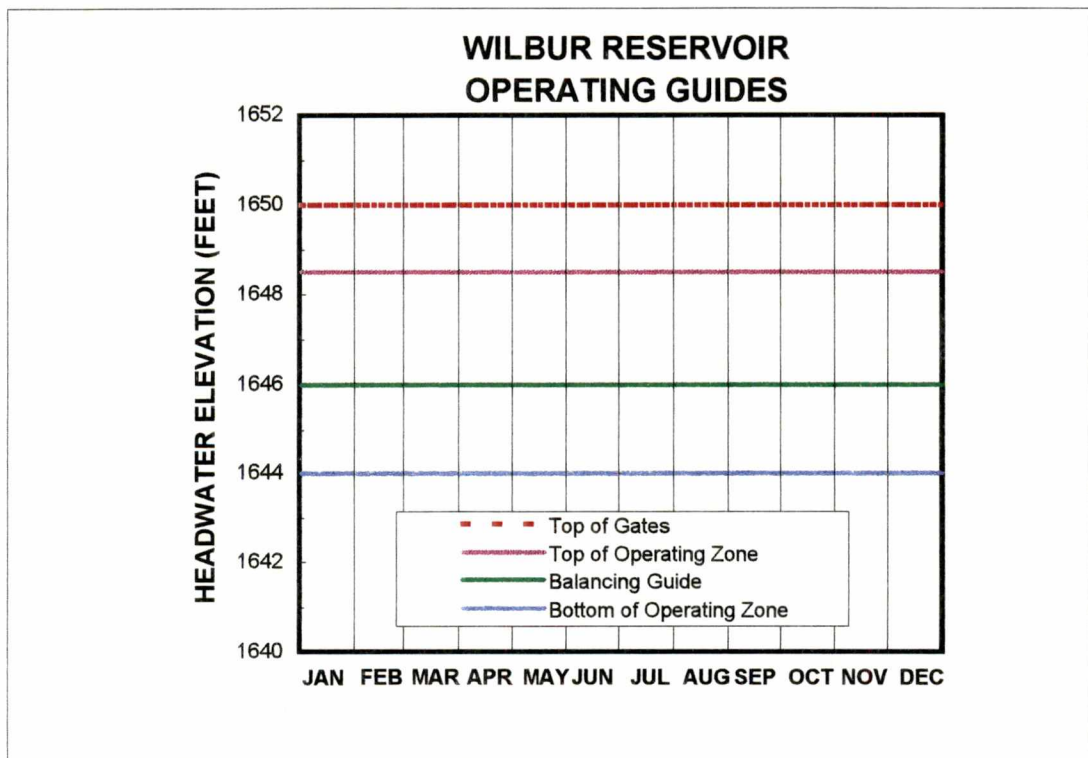


Figure 7. Wilbur Reservoir Operating Guides.

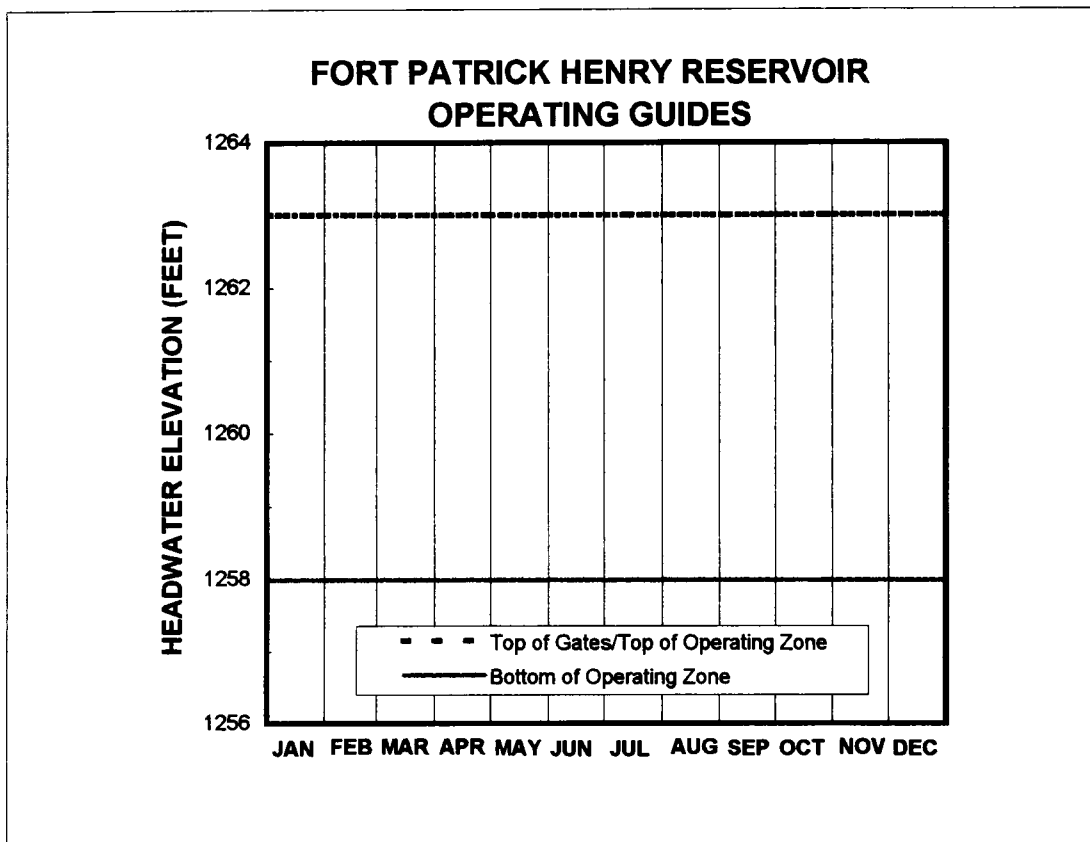


Figure 8. Fort Patrick Henry Reservoir Operating Guides.

V. RiverWare Description

RiverWare is a computer modeling framework developed by the Center for Advanced Decision Support for Water and Environmental Systems (CADSWES) at the University of Colorado under sponsorship of Tennessee Valley Authority and U. S. Bureau of Reclamation. Prior to TVA's involvement in this development project, models used in operating the Tennessee River system were all developed in-house by TVA engineers. These models were written using FORTRAN for specific reservoirs within the TVA system. There was no flexibility for reservoir operators to change model timesteps or other aspects of model configuration. Due to the evolving demands placed on the TVA system and the inflexibility of the FORTRAN models being used, reservoir operators realized in the early 1990's the need to develop a software tool that would allow the user the flexibility of changing model run length, timestep, and configuration. During this time, TVA partnered with CADSWES and the U.S. Bureau of Reclamation to develop the modeling framework known as RiverWare.

RiverWare uses an object-oriented, data centered modeling approach. It is called a modeling framework because it is not a hard-coded, basin specific model. Therefore, it can be applied to any river basin. By using an object-oriented modeling approach, models of any river basin can be constructed through a graphical user interface (GUI).

The RiverWare GUI contains objects which represent pieces of modeling code written in C++. An object palette allows the user to graphically represent a river system in the RiverWare workspace. The RiverWare palette contains 15 objects, 13 of which

represent entities within a river system. Additionally, there is a thermal object which represents power economics and a data object which can be customized by the user to include equations or other information used in modeling a reservoir system (Figure 9). See the subsection of the glossary entitled “RiverWare Nomenclature” for a description of each individual object (Zagona, 1998).

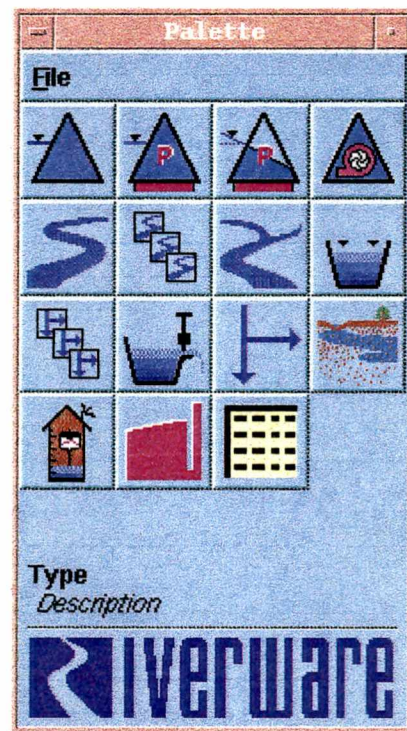


Figure 9. RiverWare Object Palette

By linking objects together, physical processes can be simulated such as mass balance in level pool reservoirs and river reach routing. Figure 10 shows the Upper Holston system which comprises five level power objects, two stream reaches, and a data object. The data centered model design allows the user to characterize each object in the workspace with specific data which is loaded into “slots” within that object. A slot

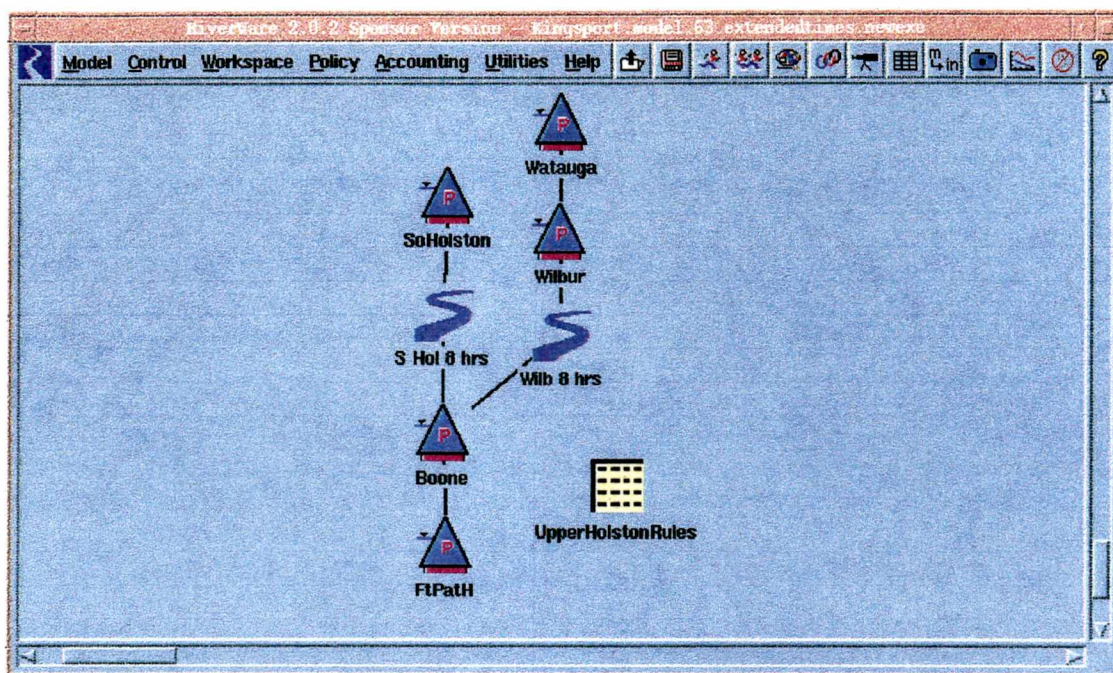


Figure 10. RiverWare Upper Holston System Model.

contains either timeseries values (timeseries slot), relational values (table slot), or simple parameter data (scalar slot).

An example of a table slot is a reservoir elevation-volume curve. An example of a timeseries slot is turbine discharge for each timestep. An example of a scalar slot is the average lag time for a river reach. The types of slots available in each object are determined by the engineering methods selected. For example, the spill computation method selected for each object reflects the types of spillways present at that project. In this example, spill calculations could include regulated spill, unregulated spill, bypass discharge (sluiceways), or a combination of the three. The slots required for each type of spillway computation are automatically added to the object when the appropriate method is selected. In addition to spillway computations, various methods are available for computing tailwater elevations, backwater elevations, river reach routing, and several

other types of calculations. Table 2 shows selected user methods in RiverWare (Zagona, 1998).

Timeseries slots can be set to either user inputs or outputs. When enough inputs are set by the user for a given object, such as inflow and outflow, that object will “dispatch” during a model run. By dispatching, the object solves the mass balance to compute any unknowns such as storage in this example. Objects dispatch for each timestep of the model run. Timesteps can be set by the user to hourly, six-hourly, twelve-hourly, daily, weekly, monthly, or yearly. The user must decide which timestep will provide enough precision without becoming computationally too time consuming. The length of the model run is also user defined. The run length is usually based on the length of the study being conducted or the length of time for which there is adequate input data, i.e. forecasted inflows.

There are three run controllers available in RiverWare. These run controllers are simulation, rulebased simulation, and optimization. The subject of this thesis is rulebased simulation, therefore this modeling method will be discussed in detail in the remainder of this section.

Table 2. Selected User Methods in RiverWare.

OBJECT TYPE	USER METHOD CATEGORY	USER METHODS	
Reservoirs	Spill	Unregulated Spill Regulated Spill Unregulated Plus Regulated	Regulated Plus Bypass Unregulated Plus- Regulated Plus Bypass
	Tailwater	Tailwater Base Value Only Lookup Table	Tailwater Stage Flow Tailwater Base Value Plus- Lookup Table
Reaches	Routing	No Routing Time Lag Routing Variable Time Lag Routing	Muskingum Kinematic Wave Muskingum-Cunge MacCormack

Rulebased simulation allows the user to “direct the simulation of a river network via operating policies or rules” (Wehrend, 1997). “There are four components of RiverWare that make up rulebased simulation: a rule language, a set of GUI-based rule utilities, a rule processor, and a rulebased simulation controller. The first two components are used directly by RiverWare users to create, modify and debug rules. The remaining components are used internally by RiverWare to execute rules and control the simulation” (Wehrend, 1997).

Rules can be written by a user through a rule editor called the “Rule Palette”. This rule palette “is a dynamic dictionary of elements with which expressions can be constructed” (CADSWES, 1997). Although a user can construct rules using the rule palette (Figure 11), the rules are actually coded using tcl (tool command language). The rule palette allows a user unfamiliar with the tcl programming language to write rules.

A “Ruleset”, or a set of rules used in a model, contains “Policy Groups” which are simply groups of rules that are arranged together for a particular reason, for example they may all pertain to the same reservoir. A ruleset can contain multiple policy groups and a policy group can contain multiple rules. For example, a ruleset defined for the Upper Holston system model could contain one policy group for each of the five reservoirs in the system. Within each policy group, there can be many rules. Multiple policy groups could be used in a large ruleset where it would be more convenient for the user to associate certain rules with one another. Figure 12 shows the Upper Holston ruleset which contains only one policy group, the Upper Holston policy group, which is being used in this study.

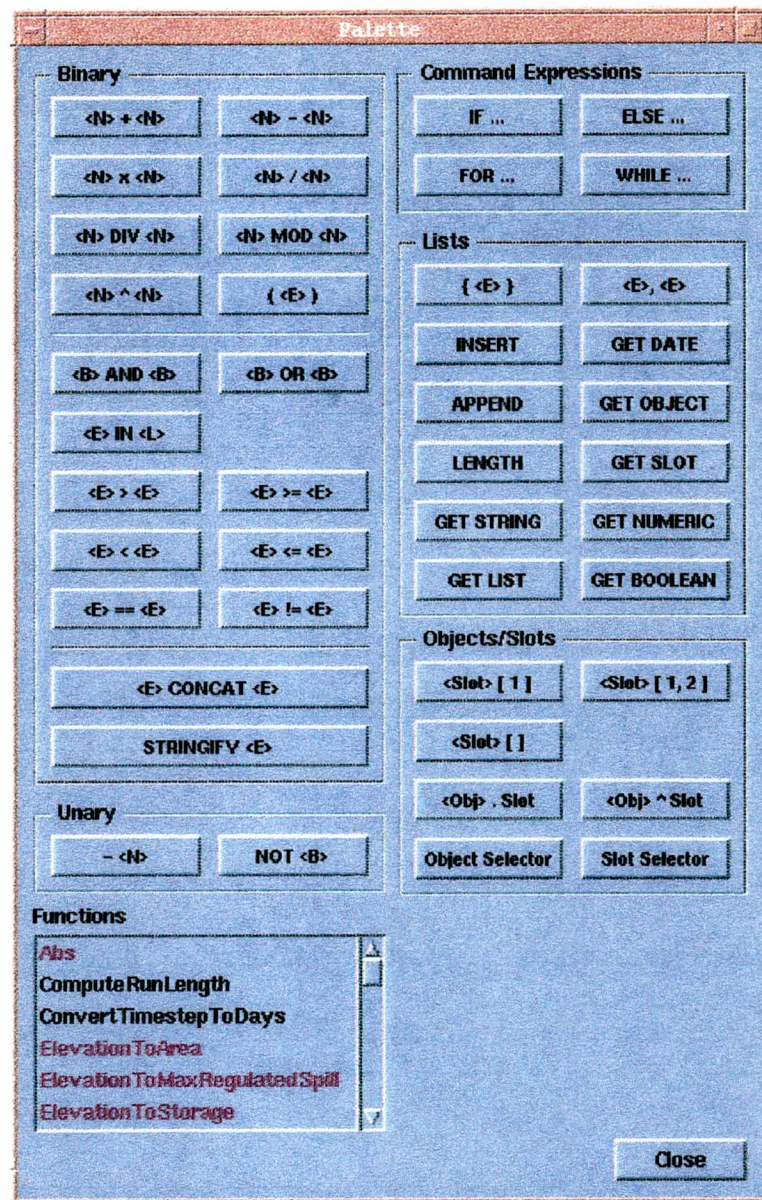


Figure 11. RiverWare Rule Palette.

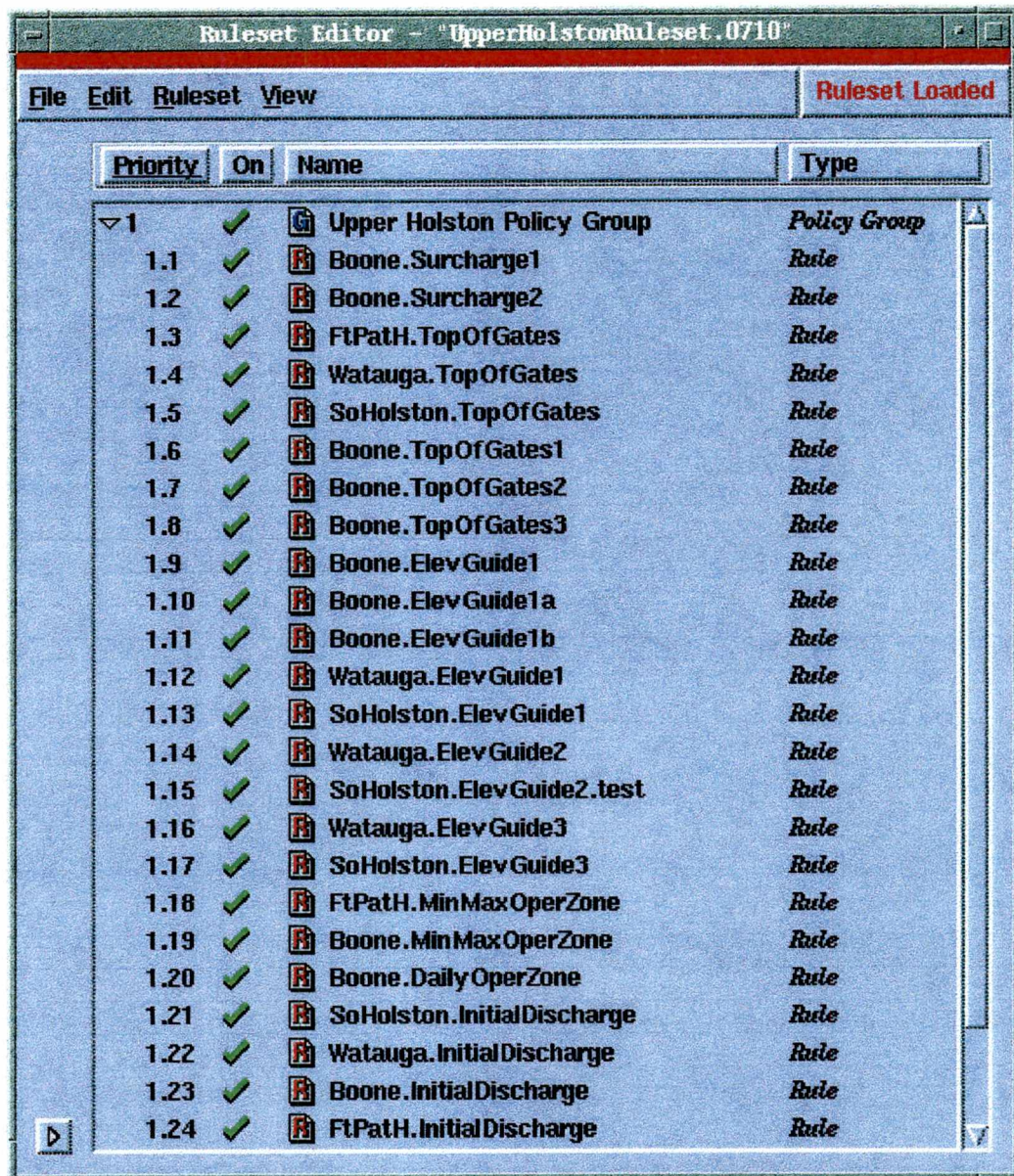


Figure 12. RiverWare Upper Holston Ruleset Policy Group.

Each policy group is assigned a priority within the ruleset. For instance, the Upper Holston policy group is assigned priority 1. If there were more than one policy group within the Upper Holston Ruleset, the remaining policy groups would be assigned priorities 2, 3 and so on. Each rule within a policy group is assigned a priority. Referring to Figure 12, the highest priority rule, "Boone.Surchargel" is assigned priority 1.1. This refers to the policy group priority first and the rule priority within that policy group second. The fifth highest priority rule is assigned priority 1.5, which in this case is "SoHolston.TopofGates". This again refers to the policy group priority first and the rule priority second. It is the responsibility of the user to define the relative importance or priority of each rule.

Statements within the rule assign a numeric value to timeseries slots. This value can come from another timeseries slot, a table slot, or an internal or external function. Functions, which are calculations executed by a rule, return values to the rule from which they are executed. The rule then assigns these values to the appropriate slot within an object. An internal function is defined internally within RiverWare, and the code cannot be directly accessed by the user. These functions are generic calculations that are commonly utilized by RiverWare users. An example of an internal function is "ElevationToStorage". This function computes a storage value for a given elevation. An external function is user defined. External functions are usually written for a specific reservoir or basin and often cannot be generalized. An example of an external function is "OutflowToMeetMax" used in the Upper Holston ruleset. This function takes the

current elevation, a given target elevation, and predicted inflow and computes the discharge required to reach this target.

Internal and external functions can be contained in either a policy group or a utility group. If a function is contained in a policy group, it can only be accessed by that policy group. A utility group contains functions that may be used by any other functions, policy groups, or rules within the ruleset. Figure 13 shows the utility group used in the Upper Holston ruleset.

The rule processor proceeds through the group of prioritized rules at each timestep. The rules execute in the order of highest priority to lowest priority. Again, it is the responsibility of the user to define the relative importance of each rule when writing the ruleset. Each rule assigns a value to a slot. After a slot within an object is set to a specified value by the rule, the run controller switches from rulebased simulation to simulation. The objects within the workspace that have enough information to dispatch do so. The rule processor then proceeds to the rule of the next highest priority. When all rules have executed for a given timestep, the controller proceeds to the next timestep. This process is repeated for the entire length of the model run. At no time during the model run can a rule set a value that has been previously set by a higher priority rule. User inputs carry the highest priority (level 0) and cannot be overwritten.

The user can enable or disable any rule or function within the ruleset with a simple mouse click. Rules can also be re-prioritized using the mouse by dragging the rule either up or down the list to its new location within the GUI. This enables the user to test various modeling scenarios by eliminating some rules or rearranging rulesets.

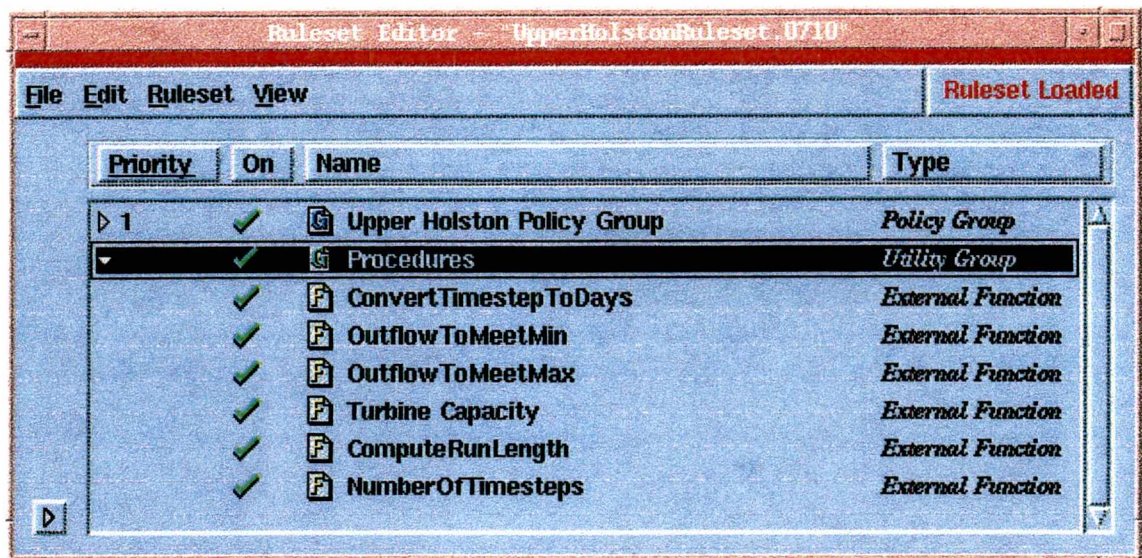


Figure 13. RiverWare Upper Holston Ruleset Utility Group.

VI. Modeling the Upper Holston System

The elevation and discharge guides for each of the projects in the Upper Holston system are represented in the RiverWare rulebased simulation models in the form of prioritized rules. Each rule is formulated using an if-then statement. The antecedent (if clause) is pool elevation and the value being set by the rule is outflow. For example, if the headwater elevation at a given project is above a specified elevation guide, then the discharge from that project is set to a value specified by the rule. An example rule window is shown in Figure 14.

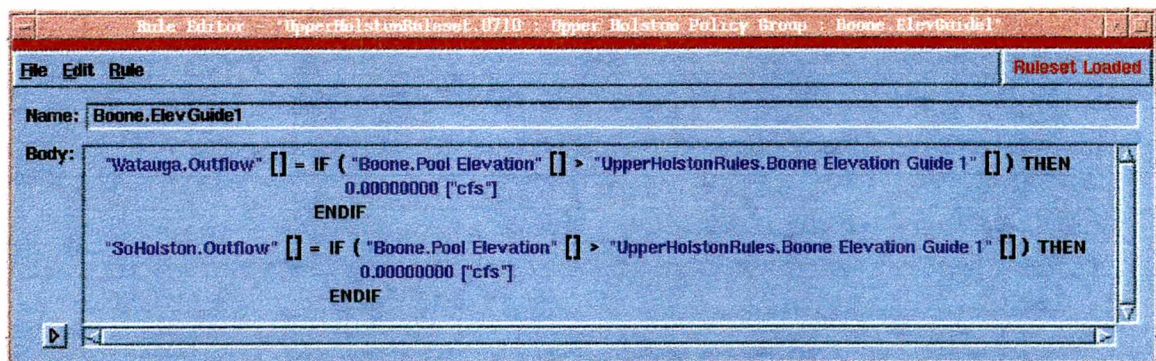


Figure 14. RiverWare Example Rule from Upper Holston Ruleset.

The highest priority operating objectives are given the highest priority in the ruleset. The controller dispatches all objects that it can given user (level 0) inputs. When there are no objects left to dispatch given user inputs, the controller begins at the top of the ruleset (priority 1) and tries to execute the rules in order of priority. Because each of the rules is formulated using an if-then statement, the antecedent of each rule (pool elevation) is usually unknown at the beginning of the timestep. If the antecedent is unknown, the controller proceeds to the next rule until it finds one that can be executed.

In the Upper Holston ruleset, rules 1 through 20 are all formulated using if-then statements and cannot be executed until the antecedent is known. In order for the objects in the workspace to dispatch and solve for all unknowns, an initial or starting point discharge is set for each object via rules 21 through 24. These rules are the only ones in the ruleset that are not formulated using if-then statements. They simply set an outflow for the respective project which allows the object to dispatch. Then, the object is dispatched given inflow and outflow and all remaining variables are solved.

Once an object has dispatched, the controller starts over with priority 1 and attempts to execute those rules that apply to that object. For example, the South Holston initial discharge for the first timestep is set by rule 21. The South Holston object then dispatches and solves for all unknowns. The run controller then starts at the top of the ruleset and executes those rules that apply to South Holston. In this example, rules 1 through 4 would not be executed (fail) because they do not apply to South Holston and rule 5 would be executed if applicable. The rule states that if South Holston elevation is computed to go above top of gates elevation based on the initial value set by rule 21, then set a new discharge. This rule would only execute if the elevation computed using the initial discharge were above top of gates. If not, the controller would proceed to the next rule that applies to South Holston. Once all of the rules that apply to South Holston are either executed or fail, the controller proceeds to the rule of the next highest priority in the ruleset. The controller would proceed in the same manner until all objects are dispatched and all rules are satisfied for that timestep. Then the controller would proceed to the next timestep. A flow chart describing the Upper Holston ruleset used in this study

is shown in Figure 15. Each diamond in the flow chart represents a rule, and each parallelogram represents a value or values being set by a rule.

The RiverWare Upper Holston models were tested with observed inflows from three different high flow events. The above procedure is applied to each of these models. These events were selected because high inflows caused high headwater elevations and increased discharges in the Upper Holston watershed. The same ruleset is applied to each model; however, the initial conditions and observed inflows are set to exactly replicate what actually occurred. A discussion of actual elevations and discharges as well as modeled elevations and discharges will be presented in the following section.

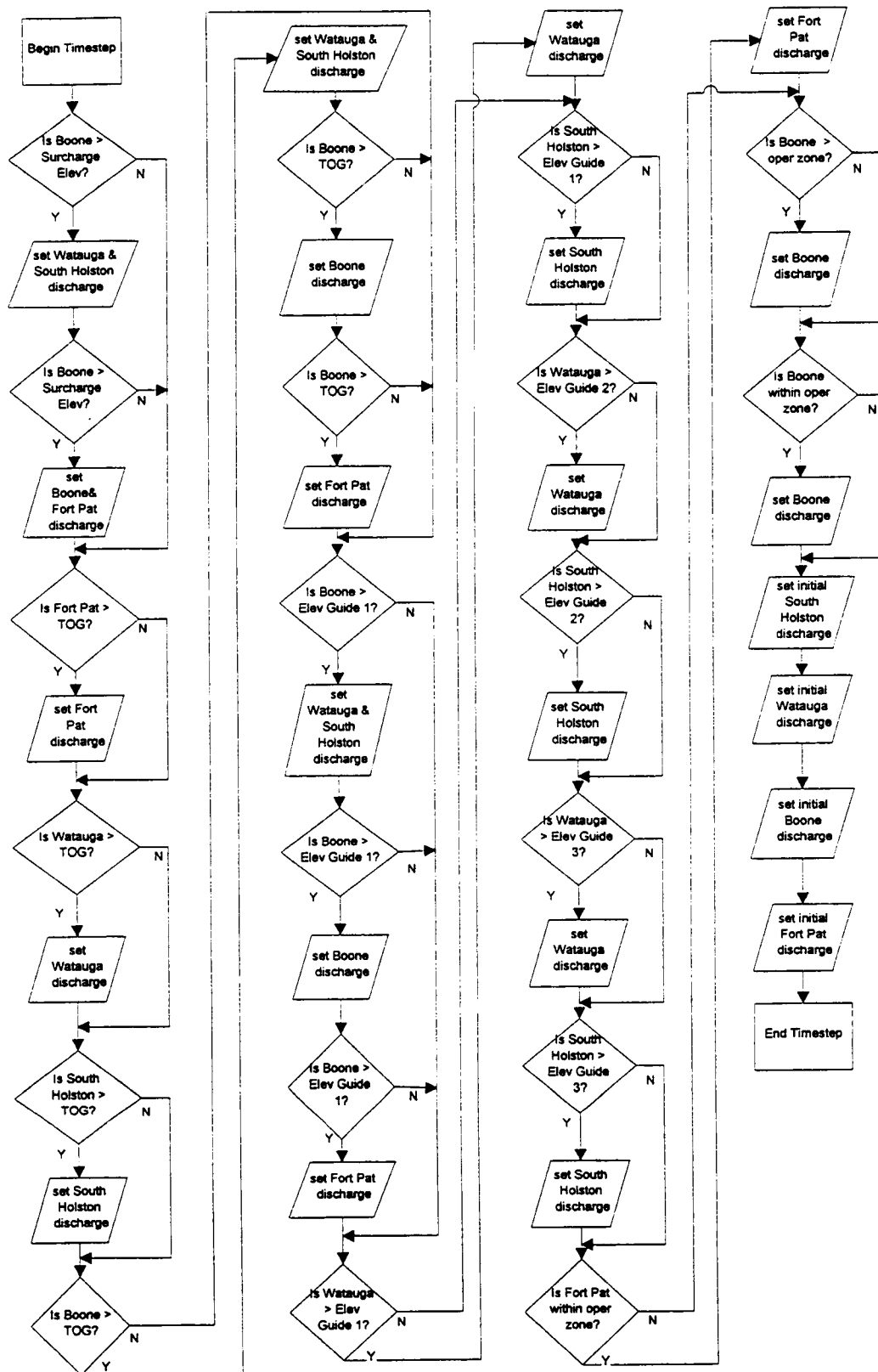


Figure 15. Schematic Diagram of the Upper Holston Ruleset.

VII. Discussion of Observed Events and Rulebased Simulation Model Results

Many changes that impact reservoir scheduling have occurred over the years, including changes in operating policy, refined weather forecasting, and software innovation. The ruleset used in this investigation reflects the current operating constraints placed on the system, which may differ from years past. Also, as previously stated, this ruleset was written to reflect operating constraints on the Upper Holston system, without regard for impacts to the remainder of the Tennessee Valley. The entire Tennessee system is not modeled, and therefore, these impacts cannot be determined. For these reasons, a parallel between actual operations and modeling results should not be expected. Also, the Upper Holston ruleset was written based on one person's interpretation of the operating constraints placed on the Upper Holston system. A similar ruleset based on another interpretation or personal experience could yield different results.

The selected storm events modeled for this study occurred during March 1963, April 1987, and February 1994. Discharges from Fort Patrick Henry reservoir were greater than 11,500 cfs during each of these storms. The highest elevation of record occurred at Watauga on April 19, 1987 when the headwater reached elevation 1963.28 feet above msl. Eight days later, on April 27, 1987, the highest elevation of record occurred at South Holston. The headwater reached elevation 1736.92 feet above msl.

These three storms were chosen for this investigation for several reasons. The three most important reasons for choosing these storms are: 1) Most floods occur in the

Tennessee Valley during the late winter and early spring. This is true for the Upper Holston system as well. For the period that record is available, there have been no flooding events during the summer or fall that have covered the entire Upper Holston system. 2) In each of the three storms chosen, the discharge from Fort Patrick Henry exceeded the critical point of 11,500 cfs. Above this discharge, there is a potential for flood damage in Kingsport, Tennessee. 3) Unusually high headwater elevations occurred at South Holston, Watauga, and Boone for each of the three months in which these storms took place. For example, the highest headwater elevation at South Holston during March of 1963 was 1722.7 feet above msl. This is actually lower than the normal summer pool elevation of 1729 feet above msl. However, for the month of March, this headwater elevation is unusually high. Headwater elevations along with guide curves for South Holston, Watauga, and Boone reservoirs are shown in Figures 16, 17, and 18, respectively for each of the three years discussed above. The discharge from Fort Patrick Henry dam for each of the three years discussed above is shown in Figure 19.

The Upper Holston ruleset could best be tested by using several different initial conditions, which refers to beginning elevations and discharges. Therefore, actual flood events were chosen which not only represent various time periods during the late winter and early spring, but also represent a variety of initial conditions. Operation of Wilbur dam was not directly addressed in any of the models because there is virtually no flood storage space available in the reservoir. The full-pool storage in Wilbur reservoir is 595 acre-feet, which is less than 0.1 percent of the storage available in either South Holston or Watauga reservoirs. Therefore, all inflow is assumed to be passed through the

reservoir while maintaining a steady headwater. Also, because there is very little flood storage space available in Fort Patrick Henry, the elevation is initially set at 1263 feet above msl in each model run and all inflow is passed through this reservoir as well. The storage in Fort Patrick Henry reservoir is 26,900 acre-feet, which is only 4 percent of the available storage in South Holston and less than 5 percent of the available storage in Watauga.

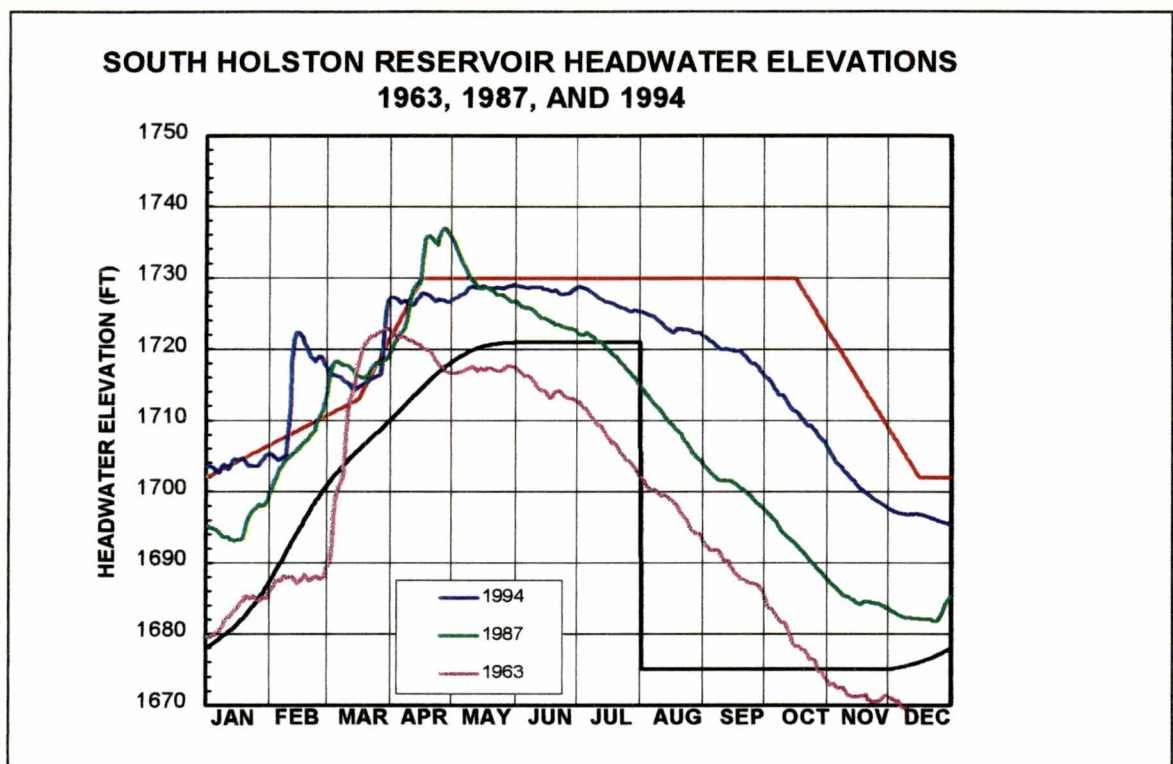


Figure 16. South Holston Observed Headwater Elevations from 1963, 1987, and 1994 Along with Minimum Operation Guide and Flood Guide.

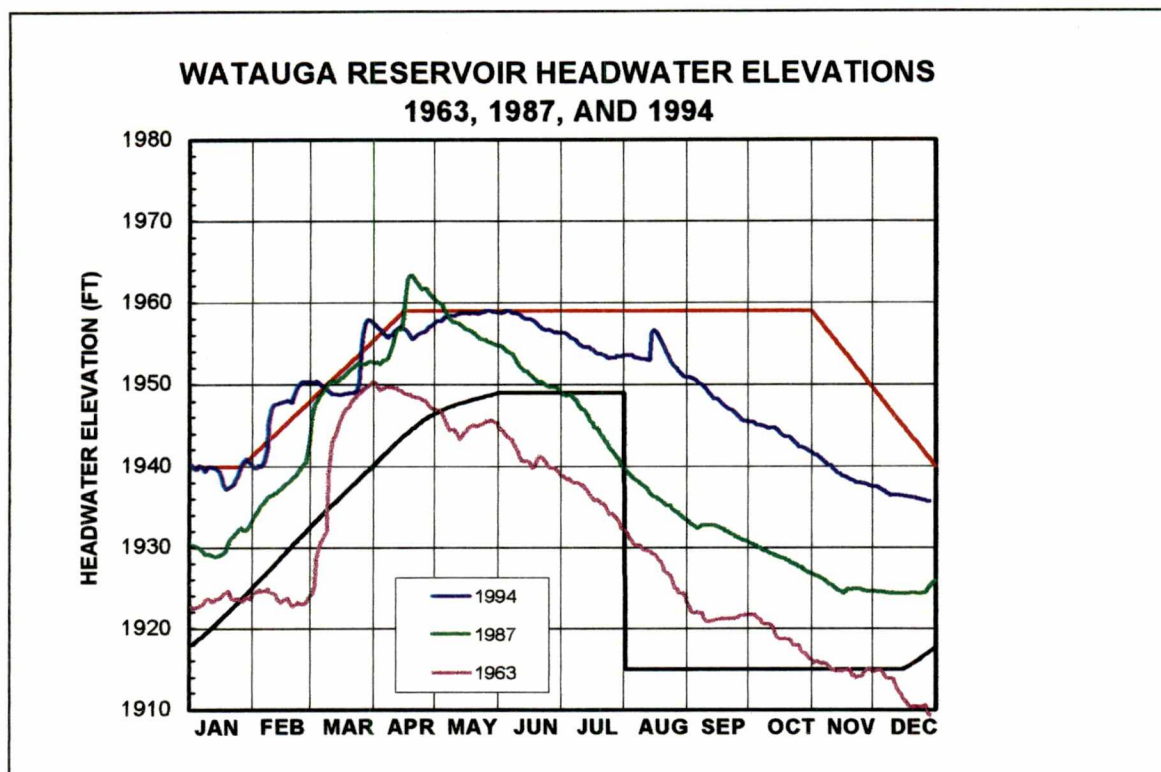


Figure 17. Watauga Observed Headwater Elevations from 1963, 1987, and 1994 Along with Minimum Operation Guide and Flood Guide.

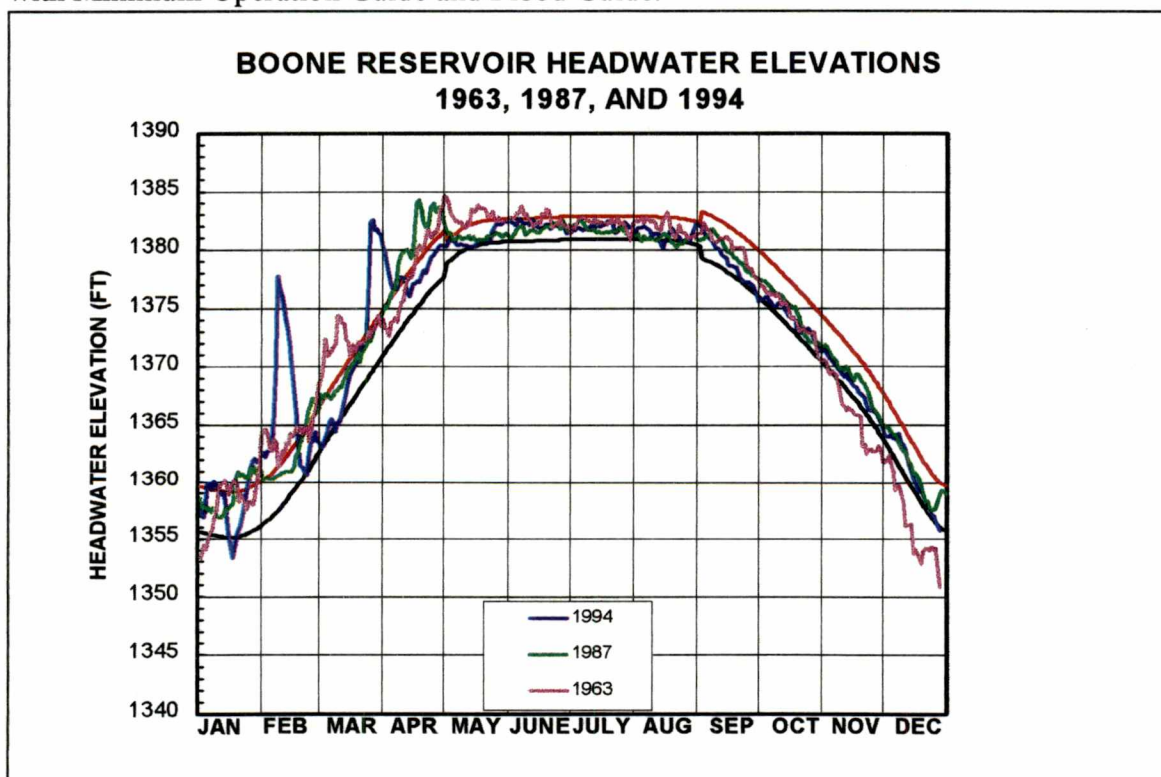


Figure 18. Boone Observed Headwater Elevations from 1963, 1987, and 1994 Along with Daily Operating Guides.

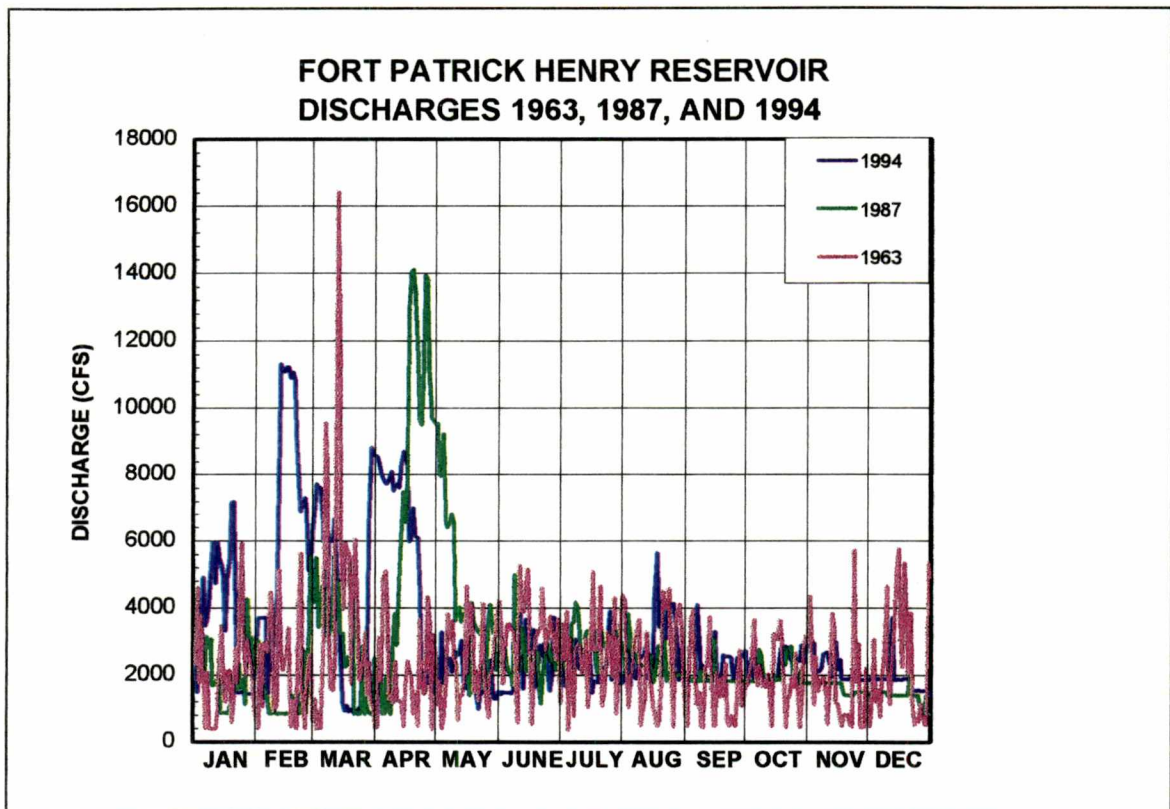


Figure 19. Fort Patrick Henry Observed Discharges from 1963, 1987, and 1994.

March 1963: Actual Reservoir Operations

During March 1963, there were two high inflow events in the Upper Holston watershed. The first occurred on March 5-6 and the second occurred on March 11-12. Rainfall amounts averaged about three inches over the area during the first storm and three to four inches during the second storm. The resulting inflow hydrographs can be seen in Figure 20. During the first event, discharges from Fort Patrick Henry exceeded 13,000 cfs. The storage reservoirs, South Holston and Watauga, were allowed to fill approximately twelve feet and six feet, respectively. The elevation at Boone reservoir increased over two feet. The headwater elevations at both South Holston and Watauga at the beginning of the first storm event were very low compared to today's standards.

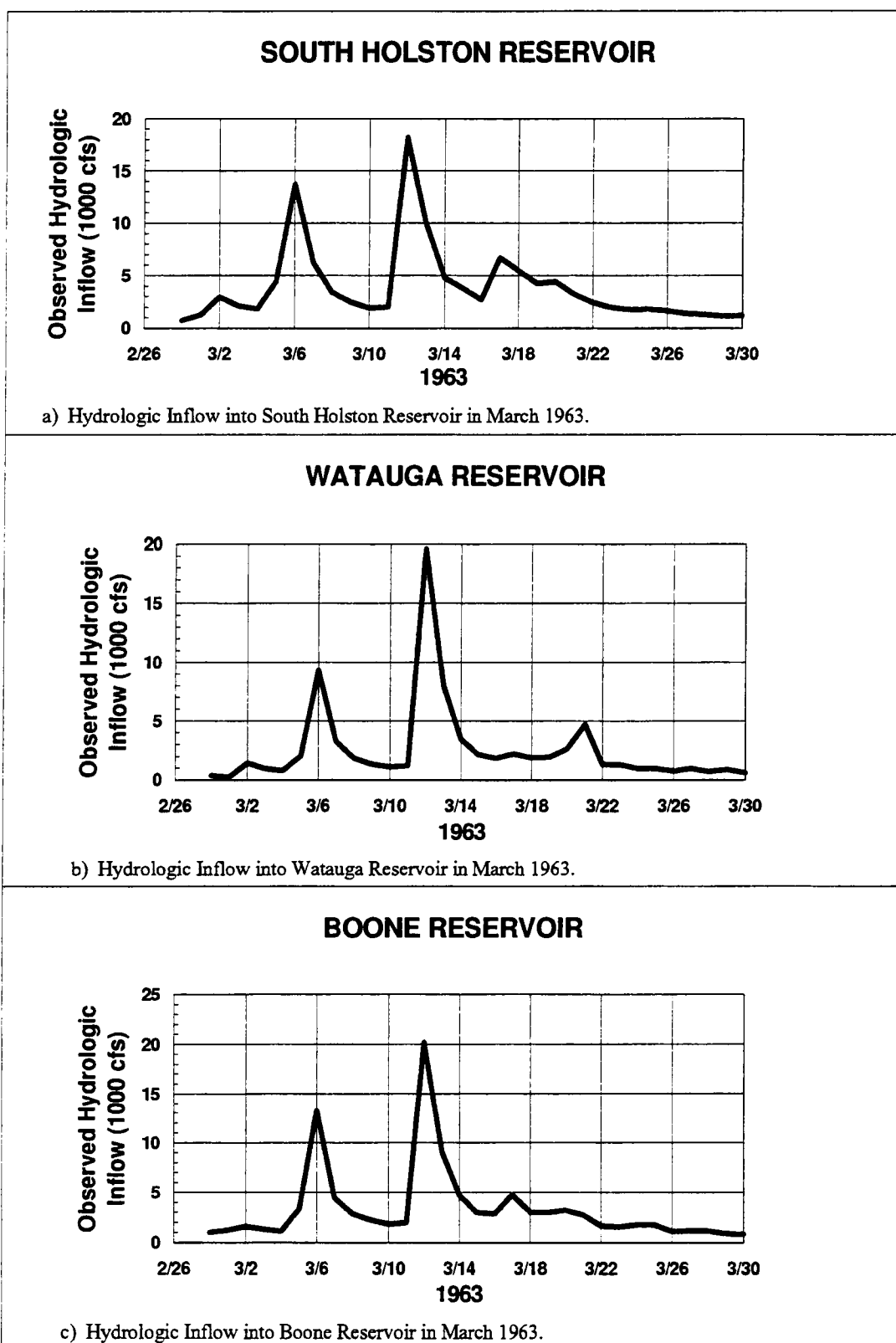


Figure 20. Hydrologic Inflow Hydrographs from Storms Occurring in March 1963.

Minimum operation guides had not been established at that time. Therefore, a great deal of flood storage space was available that could not be utilized if this storm occurred today. As a result of the second inflow event, headwater elevations at South Holston and Watauga both increased approximately thirteen feet, and the headwater elevation at Boone reservoir rose about three feet. The second storm caused elevations to exceed the flood guide at South Holston, but not at Watauga. However, the headwater elevations at both South Holston and Watauga were drawn to within the desirable operating range (below the flood guide) during the latter part of March and the first part of April. Boone's headwater elevation was higher than the daily operating range that is used today and remained so throughout the first two weeks of March. The discharge from Fort Patrick Henry exceeded 23,500 cfs on March 12 which is well above the discharge, 11,500 cfs, that begins to cause flooding in Kingsport, Tennessee.

March 1963: RiverWare Rulebased Simulation Reservoir Operations

An examination of rulebased simulation results shows that the modeled operation of South Holston and Watauga reservoirs closely parallels actual operations (Figures 21 and 22). Both the model and actual operations reflect the large amount of storage space available at the beginning of the first storm. One difference in modeled and actual operations is that discharges from Fort Patrick Henry dam do not exceed 11,500 cfs using the Upper Holston ruleset. The current ruleset holds discharges from Fort Patrick Henry dam constant at turbine capacity for a longer period of time than what was actually observed as opposed to spilling excess water initially and then returning to a normal

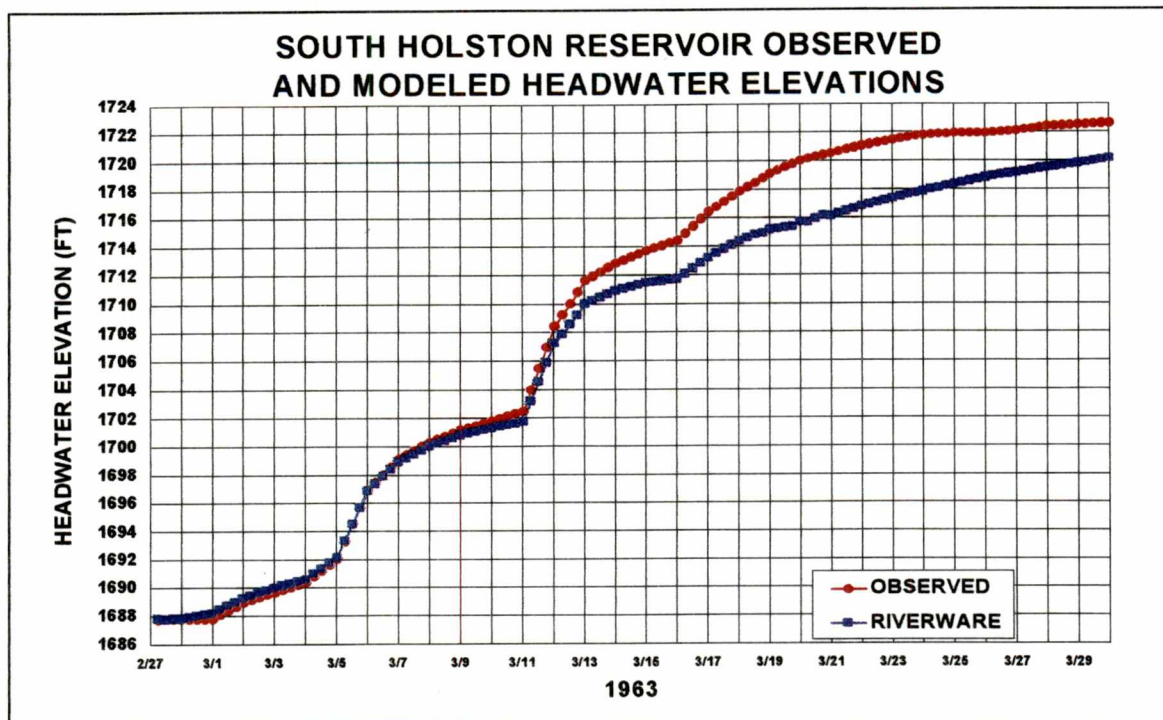


Figure 21. 1963 Observed and Modeled Headwater Elevations at South Holston Dam.

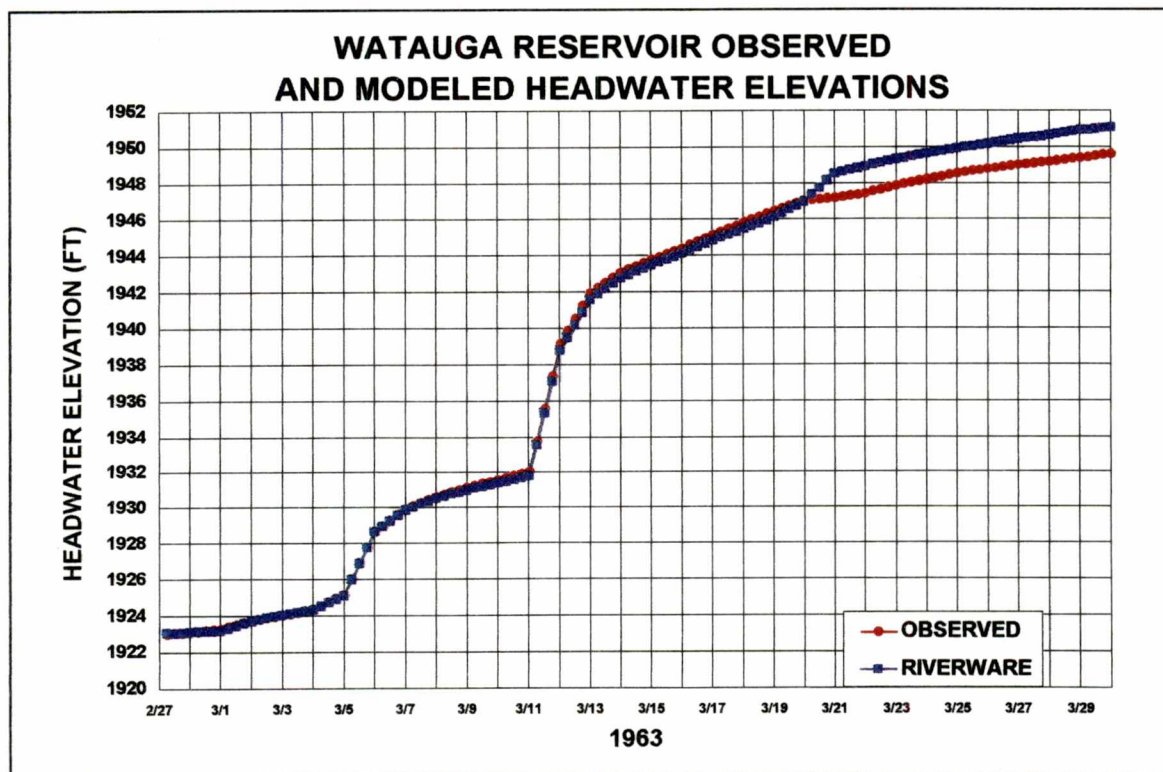


Figure 22. 1963 Observed and Modeled Headwater Elevations at Watauga Dam.

peaking pattern (Figure 23). A peaking pattern refers to operation of the turbines at a hydro plant in accordance with peaks in power demand, which typically occur in the morning and late afternoon during this time of year. This allows more water to be discharged from the upstream projects immediately following the second storm event, resulting in lower headwater elevations at South Holston and Boone.

Another difference is that the Upper Holston ruleset initially draws Boone elevation down in order to operate the reservoir within the normal daily operating range that is used today (Figure 24). This involves increasing discharges above observed amounts from Boone, and therefore Fort Patrick Henry reservoir, at the beginning of the model run, March 1. However, this increased discharge does not exceed turbine capacity at Fort Patrick Henry dam. This produces much more flood storage availability in Boone reservoir in the rulebased simulation model which is utilized during the second storm event. By utilizing this flood storage space in Boone reservoir, more water can be released from the upstream reservoirs, South Holston and Watauga.

Although the Upper Holston ruleset directs Boone reservoir to fill about 4 feet over the course of the first storm event, the desirable elevation range is quickly regained by keeping Boone and Fort Patrick Henry discharges at or near turbine capacity for about two and one half days. Because this ruleset directs the model to quickly return to the zone of daily operation at Boone reservoir, there is storage space available in advance of the second storm. In fact, rulebased simulation modeling results show Boone reservoir filling over ten feet as a result of the second storm event. However, South Holston

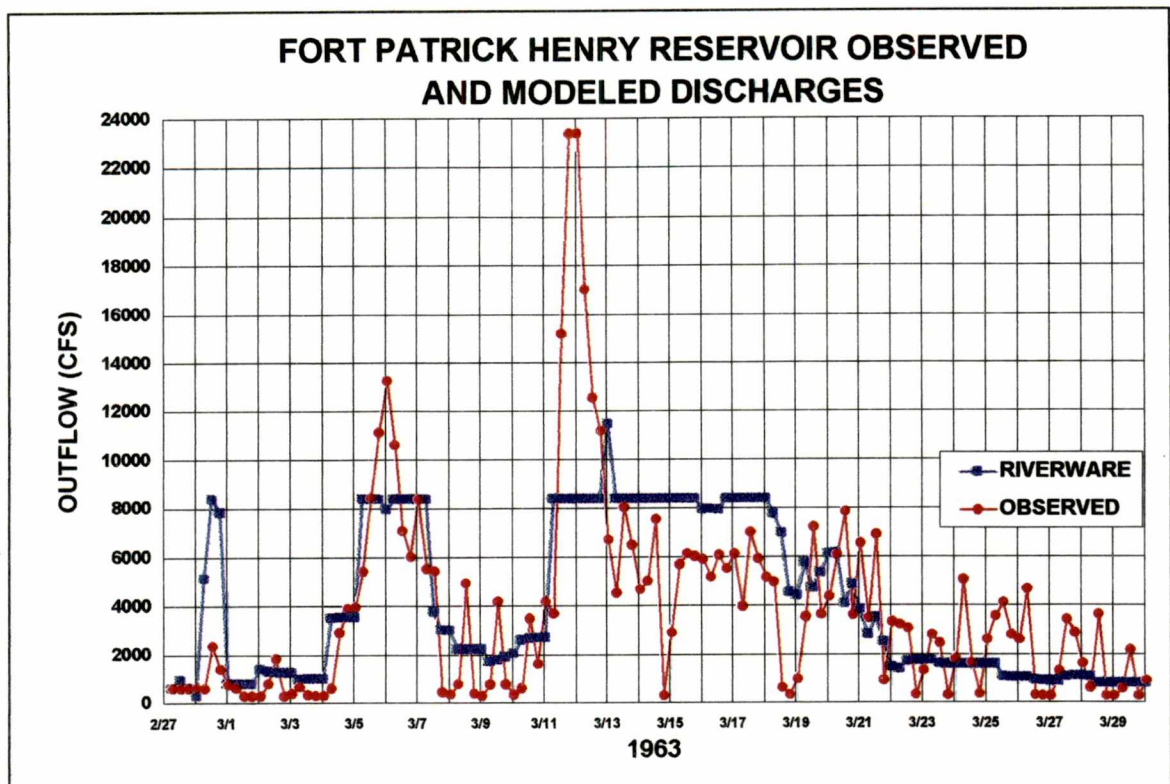


Figure 23. 1963 Observed and Modeled Discharges from Fort Patrick Henry Dam.

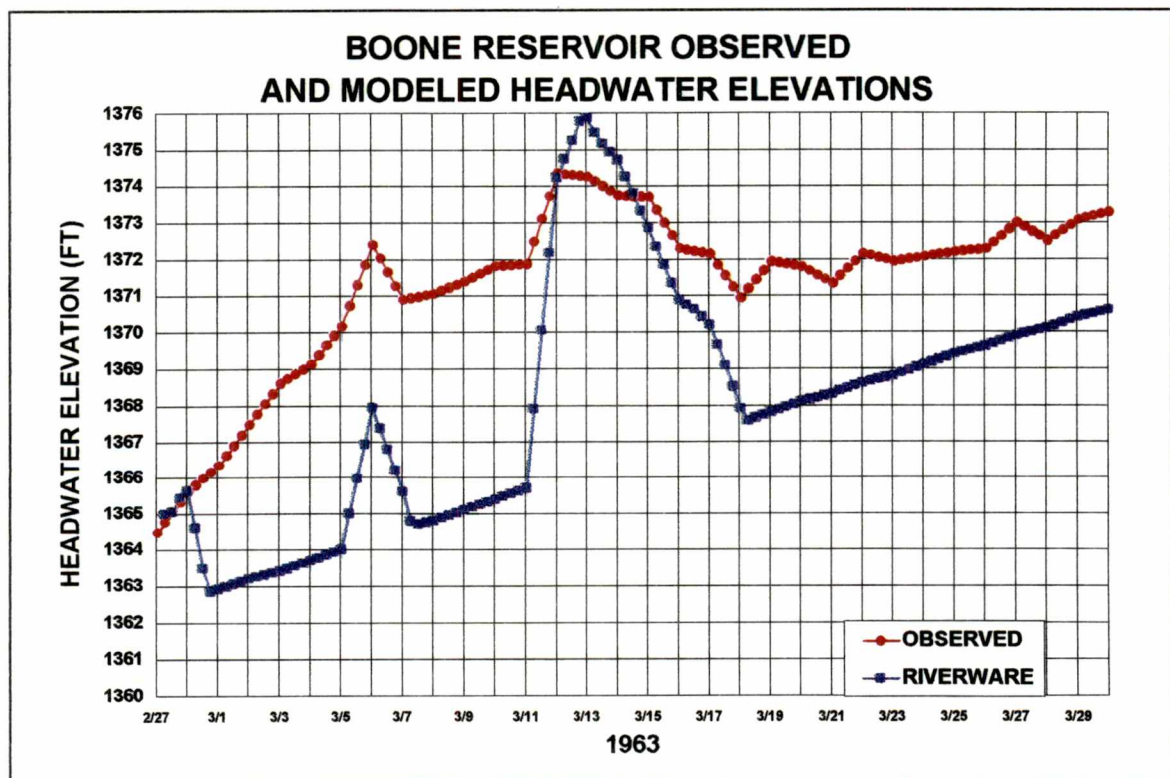


Figure 24. 1963 Observed and Modeled Headwater Elevations at Boone Dam.

increases about eighteen feet and Watauga about nineteen feet. Because much of the excess water is stored in the projects above Fort Patrick Henry, discharges from this dam were not forecast to exceed turbine capacity except for a very short period of time, and then the discharge does not exceed the critical point of 11,500 cfs.

A third difference is that there is a divergence between actual reservoir operations and rulebased simulation model operations during and following the second storm event at South Holston and Watauga reservoirs. However, this divergence is rather small, resulting in only a two foot difference in the headwater elevation at the end of the model time period at South Holston and a one foot difference at Watauga. The actual volume of water released from South Holston over the thirty day time period was approximately 27,000 acre-feet as compared with 39,000 acre-feet in model results (Table 3). This difference of 12,000 acre-feet over the 30 day period is only 2 percent of the storage capacity of the reservoir, which is 592,000 acre-feet at elevation 1720 feet above msl. The actual volume of water released from Watauga over the thirty day time period was approximately 10,000 acre-feet as compared with 4700 in model results. Here, the model released less water than actual operations, resulting in modeled headwater elevations about one foot higher than actual headwater elevations at the end of the model time period. However, when compared with the storage capacity of the reservoir, which is 512,000 acre-feet at elevation 1950 feet above msl, this difference of 5300 acre-feet is only 1 percent (See elevation-volume curves in appendix).

An explanation for the difference at South Holston is that the discharge from Fort Patrick Henry dam is higher in model results than in actual operations following the

Table 3. Comparison of Observed Daily Average Discharge and Total Volume for Upper Holston Reservoirs with Rulebased Simulation Model Discharge and Total Volume for 1963.

DAILY AVERAGE DISCHARGE (1,000 CFS) AND TOTAL VOLUME (ACRE-FEET)								
	SOUTH HOLSTON		WATAUGA		BOONE		FORT PATRICK HENRY	
Date	RiverWare	Observed	RiverWare	Observed	RiverWare	Observed	RiverWare	Observed
3/1/63	0.09	0.70	0.08	0.27	5.69	0.83	5.54	1.29
3/2/63	0.09	0.40	0.08	0.31	1.41	0.41	0.95	0.38
3/3/63	0.09	0.20	0.08	0.20	1.23	0.74	1.28	0.88
3/4/63	0.09	0.00	0.08	0.00	0.91	0.35	1.01	0.42
3/5/63	0.09	0.00	0.08	0.00	3.13	1.66	3.54	2.85
3/6/63	0.09	0.32	0.08	0.29	7.50	10.08	8.28	9.56
3/7/63	0.09	0.00	0.08	0.00	8.39	7.21	8.39	7.48
3/8/63	0.09	0.00	0.08	0.00	4.35	2.66	4.55	2.96
3/9/63	0.42	0.00	0.08	0.00	2.03	1.76	2.23	1.61
3/10/63	0.66	0.00	0.08	0.00	1.75	1.14	1.86	1.53
3/11/63	1.10	0.00	0.08	0.00	2.34	1.99	2.67	2.49
3/12/63	1.12	0.00	0.08	0.00	7.33	16.04	8.39	16.43
3/13/63	1.80	0.00	0.08	0.00	7.73	9.44	9.17	11.90
3/14/63	1.92	0.70	0.08	0.22	8.30	6.30	8.39	5.95
3/15/63	1.90	0.50	0.08	0.25	8.29	4.16	8.39	3.85
3/16/63	1.70	0.29	0.08	0.00	8.28	5.43	8.28	5.95
3/17/63	1.41	0.00	0.08	0.00	7.88	5.42	8.17	5.74
3/18/63	1.67	0.60	0.08	0.00	8.39	5.76	8.39	5.53
3/19/63	2.58	0.01	0.08	0.01	4.95	1.44	5.92	1.74
3/20/63	1.75	1.20	0.08	0.95	5.59	5.28	5.49	4.56
3/21/63	0.09	1.46	0.08	1.27	3.82	5.63	4.73	6.06
3/22/63	0.09	0.62	0.08	0.54	2.19	2.49	2.57	3.67
3/23/63	0.09	0.59	0.08	0.00	1.48	2.77	1.64	1.86
3/24/63	0.09	0.62	0.08	0.00	1.53	2.06	1.64	1.84
3/25/63	0.09	1.38	0.08	0.00	1.51	2.64	1.58	2.43
3/26/63	0.09	1.69	0.08	0.00	1.03	2.54	1.18	3.28
3/27/63	0.09	0.72	0.08	0.29	0.90	1.46	0.94	1.40
3/28/63	0.09	0.15	0.08	0.18	1.08	2.28	1.03	2.40
3/29/63	0.09	0.92	0.08	0.16	0.63	1.08	0.87	1.21
3/30/63	0.09	0.72	0.08	0.00	0.74	1.30	0.80	0.99
Total	19.65	13.79	2.40	4.94	120.38	112.35	127.87	118.24
Total acre-feet	38,900	27,300	4700	9800	238,800	222,800	253,600	234,500

second storm event. This allows more water to be discharged from South Holston which results in lower headwater elevations in the model than what was actually observed.

However, even though observed headwater elevations are two feet higher than modeled headwater elevations, these observed values are still lower than the established summer flood guide of 1729 feet above msl at South Holston. Therefore, there was no flood damage resulting from operation of the reservoir in this manner. The divergence in the observed and modeled headwater elevation at Watauga is very slight and results from only a small difference between the observed discharge and the discharge generated by the rulebased simulation model.

A final note regarding a comparison between actual reservoir operations during the 1963 flood and rulebased simulation model results is that, as stated previously, the rulebased simulation model does not take into consideration events occurring within other areas of the Tennessee Valley. Any operational decisions made at the time reflect the goal of providing flood protection not only to local areas, but to the entire Tennessee Valley, to the extent possible. Therefore, any comparison is not an attempt to second guess decisions made during actual operations. It is simply a mechanism used to determine the suitability of this software as a tool for future flood studies, not only within the Upper Holston watershed, but for the entire Tennessee Valley.

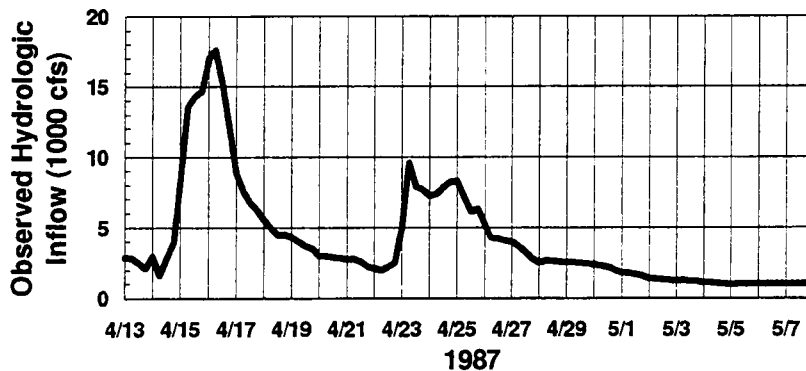
April 1987: Actual Reservoir Operations

On April 2-7, 1987 an unseasonably late snowfall blanketed the Upper Holston watershed. This snow remained on the ground until April 15-17 when a warm rain fell.

A second heavy rainfall occurred on April 24-25. The resulting inflow hydrographs can be seen in Figure 25. Following the first rain event, headwater elevations at both South Holston and Watauga rose almost seven feet. Headwater elevations at Boone reservoir rose about four feet, and the discharge from Fort Patrick Henry dam exceeded 15,000 cfs. The combined snow melt and rainfall resulted in the highest headwater elevation of record at Watauga, 1963.28 feet on April 19. Within ten days, the second rainfall resulted in the record headwater elevation at South Holston of 1736.92 feet on April 27. Also, discharges from Fort Patrick Henry dam once again exceeded 15,000 cfs, and the headwater elevation at Boone dam rose about two and one half feet. Operation of the sluiceway at South Holston began on April 17 and continued throughout the month. The headwater elevations at both South Holston and Watauga reservoirs remained above flood guides for the remainder of April. The headwater elevation at Boone also remained above the daily operating range throughout the month.

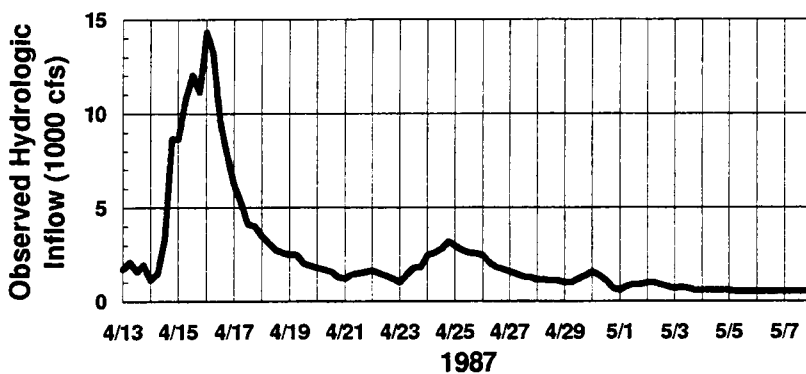
Although minimum operation guides had not yet been established for the tributary storage projects, the elevations at both South Holston and Watauga on April 15 were above the minimum levels later established in the 1990 EIS, Tennessee River and Reservoir System Operation and Planning Review. Being above the MOGs throughout the late winter and spring means that reservoir headwater elevations will likely reach the normal summer operating range, or in other words they will be at or above the MOGs at the beginning of June, because these elevation guides were established to ensure that these minimum headwater elevations could be maintained during 9 of 10 years.

SOUTH HOLSTON RESERVOIR



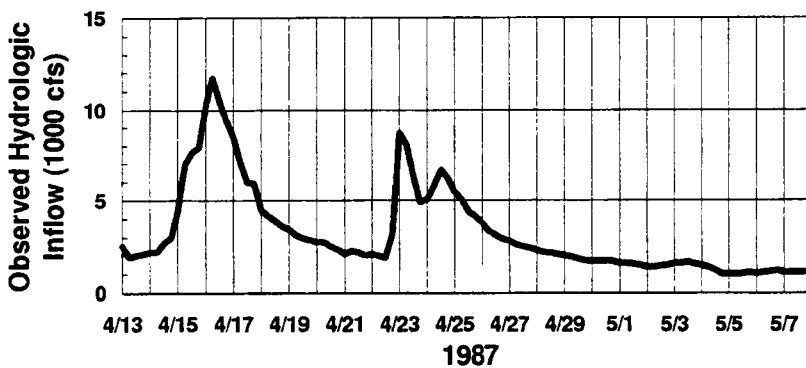
a) Hydrologic Inflow into South Holston Reservoir in April 1987.

WATAUGA RESERVOIR



b) Hydrologic Inflow into Watauga Reservoir in April 1987.

BOONE RESERVOIR



c) Hydrologic Inflow into Boone Reservoir in April 1987.

Figure 25. Hydrologic Inflow Hydrographs from Storms Occurring in April of 1987.

However, it also means that there is less flood storage space available in the reservoir than if elevations were lower.

If headwater elevations had been lower at South Holston and Watauga, obviously either more water could have been stored, resulting in the same peak elevations, or an equal amount of water could have been stored resulting in lower headwater elevations. Because the MOGs had not officially been established in 1987, there was no requirement that a minimum elevation be maintained at each project. The implication is that although it is beneficial to maintain a certain minimum elevation guide for purposes such as recreation, this is often conflicting with other demands such as flood control. Headwater elevations being higher than is absolutely necessary at the beginning of a storm could detrimentally impact the operation of the reservoir system to control flooding.

April 1987: RiverWare Rulebased Simulation Reservoir Operations

The pattern of rulebased simulation model operations closely parallels actual operations. However, modeled headwater elevations are actually higher than observed values at both South Holston and Watauga reservoirs (Figures 26 and 27). The modeled headwater elevation at Watauga reservoir is about one half foot higher than the peak of 1963.28 feet. Additionally, the rulebased simulation model drives South Holston headwater over two feet higher than the observed peak elevation of 1736.92 feet. In contrast, the headwater elevation at Boone reservoir is lower throughout the entire time period being modeled (Figure 28). The discharge from Fort Patrick Henry dam does not exceed the critical flow of 11, 500 cfs for the period being modeled (Figure 29). This

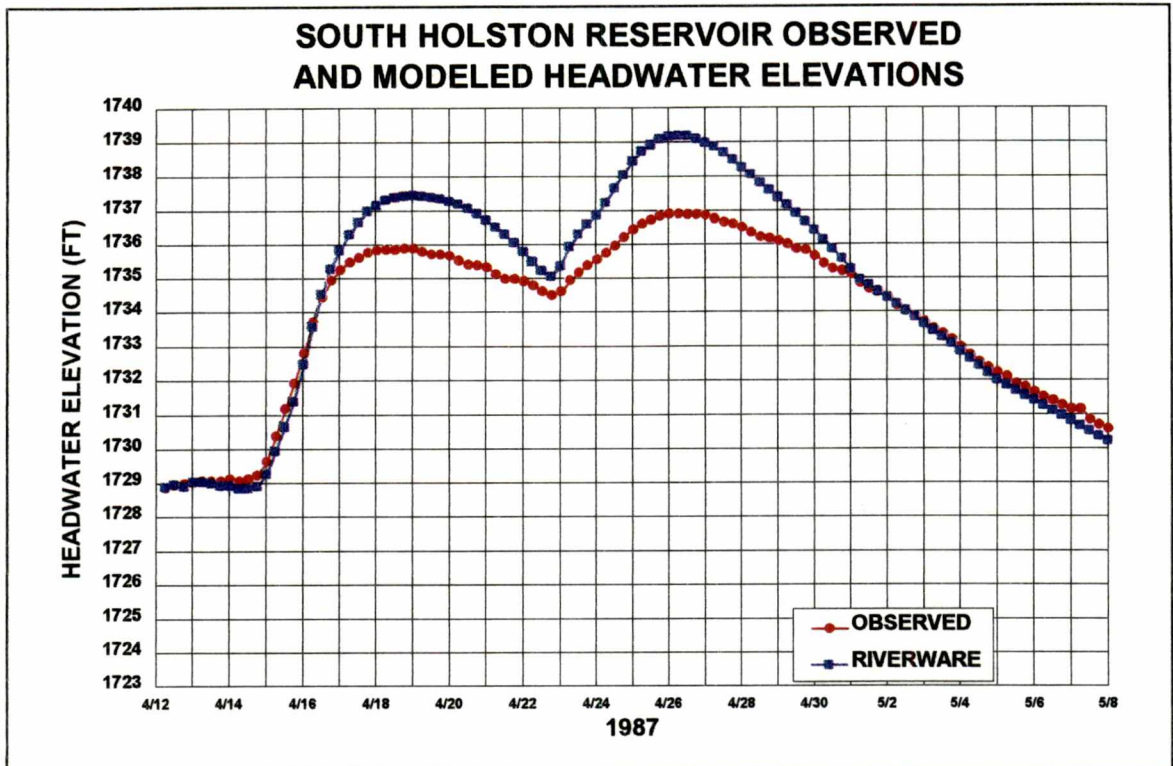


Figure 26. 1987 Observed and Modeled Headwater Elevations at South Holston Dam.

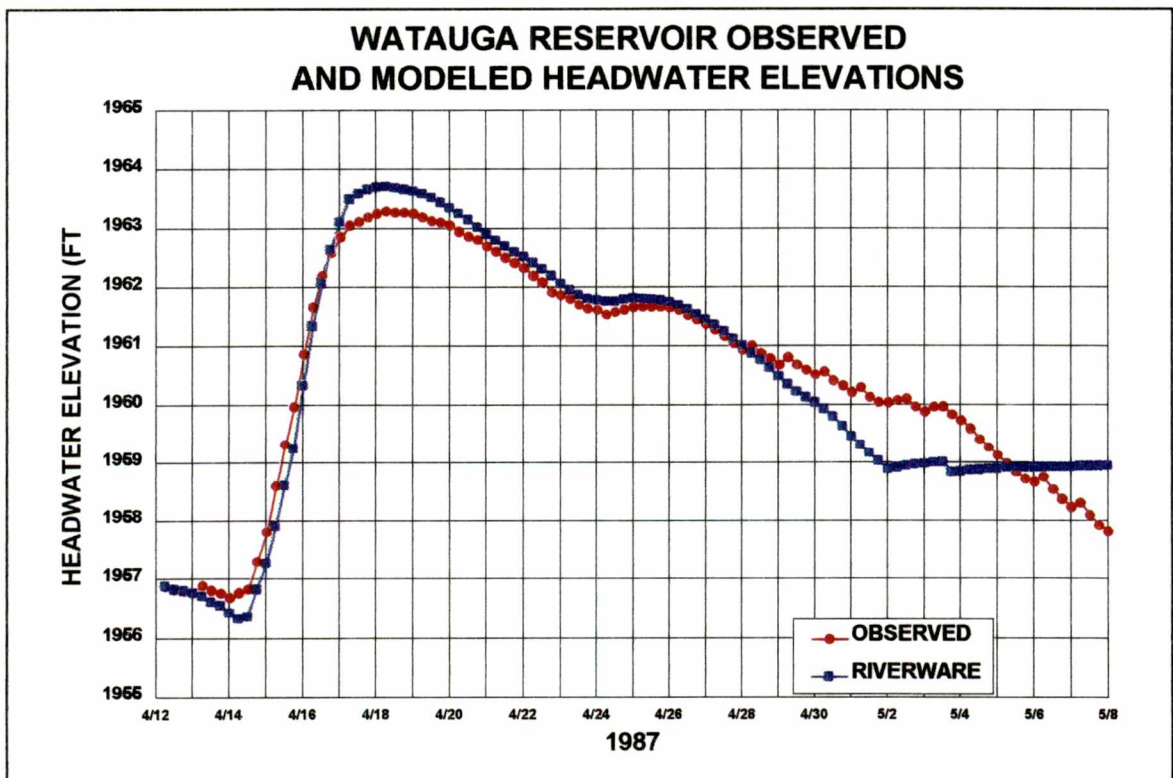


Figure 27. 1987 Observed and Modeled Headwater Elevations at Watauga Dam.

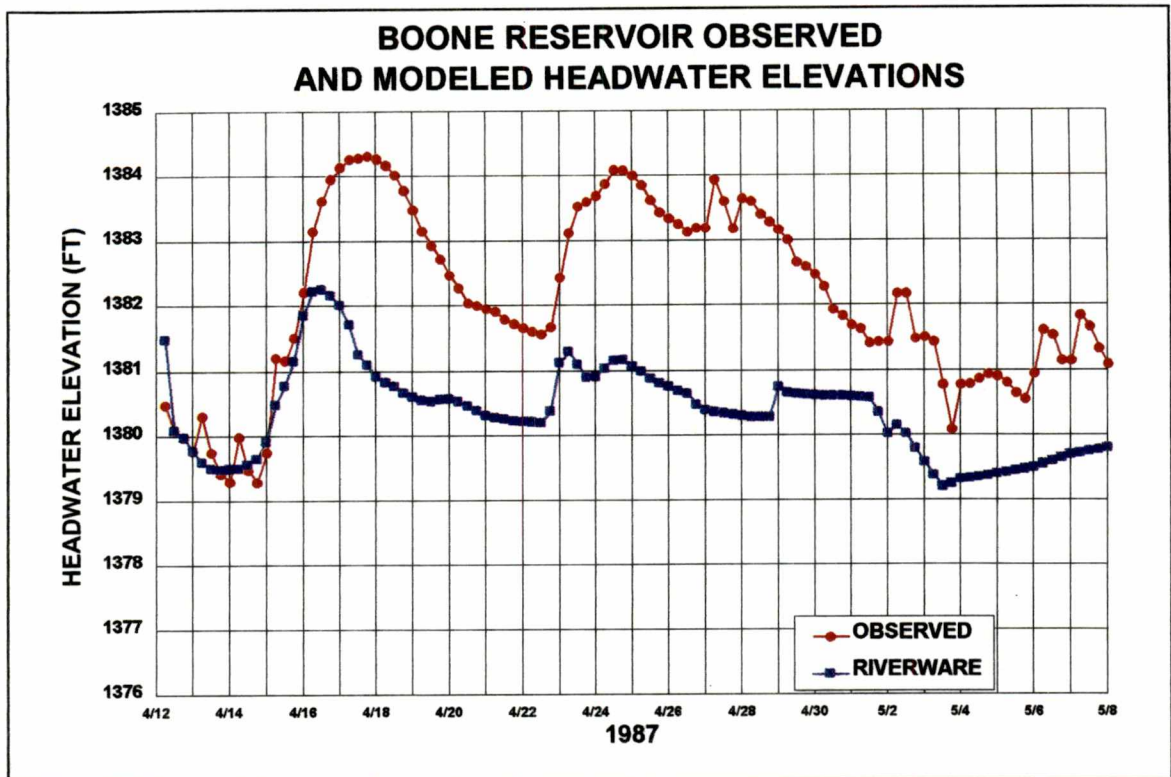


Figure 28. 1987 Observed and Modeled Headwater Elevations at Boone Dam.

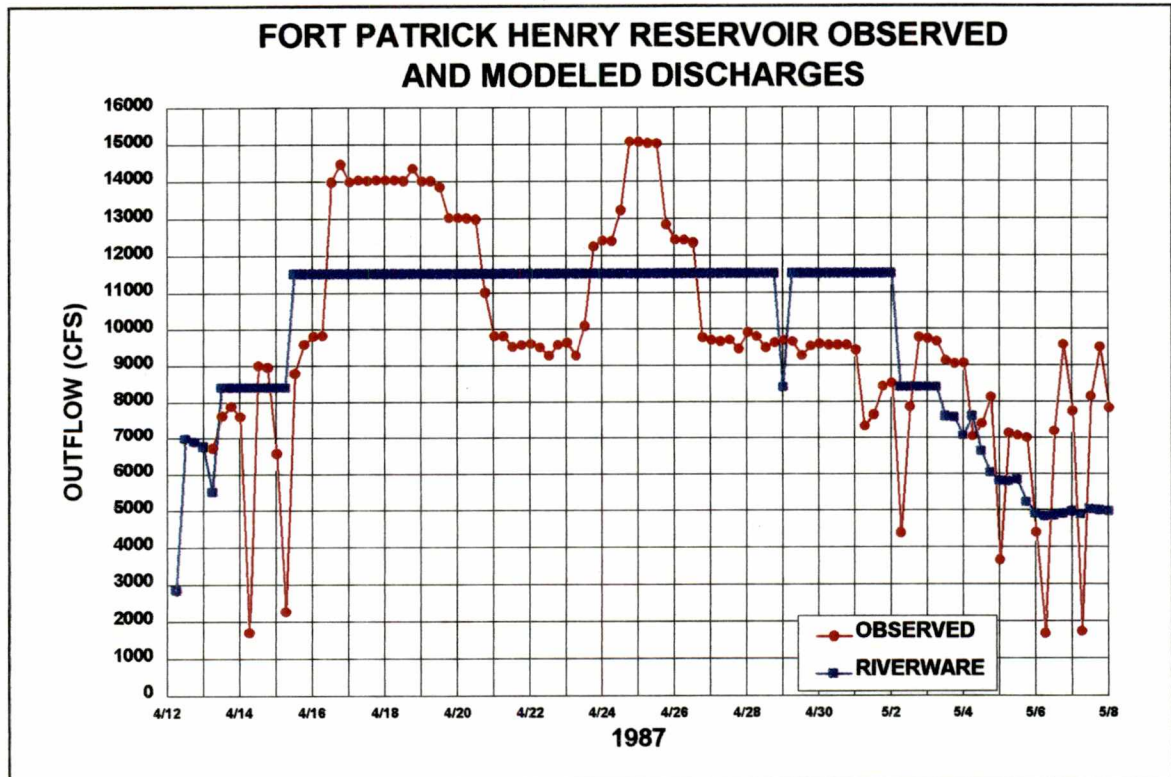


Figure 29. 1987 Observed and Modeled Discharges from Fort Patrick Henry Dam.

means that there would have been little or no flooding impacts in Kingsport, Tennessee resulting from operation of the Upper Holston system in this manner.

Even though there are some differences in peak headwater elevations at South Holston, Watauga, and Boone reservoirs, the total volume of water discharged from the reservoirs in the Upper Holston system is almost identical between rulebased simulation model results and actual operations (Table 4). The difference is that the peak elevations are higher in the upstream reservoirs, South Holston and Watauga, and lower in the downstream reservoir, Boone.

It is difficult to quantify any benefits or damage that may result from this difference in operations. An inventory of structures and infrastructure surrounding both South Holston and Watauga reservoirs was completed in 1997 (Water Management Files, 1997). Unfortunately, a similar study was not conducted for Boone reservoir. Therefore, any benefits that may have been derived by keeping the elevation two feet lower than the peak observed elevation at Boone and higher in the upstream reservoirs, such as a reduction in the number of structures impacted, cannot be determined. This study shows that at Watauga reservoir, there are approximately 25 structures that would potentially be subject to flooding when the headwater elevation reaches 1963 feet above msl. This number jumps to 96 structures when elevations reach 1964 feet above msl. The actual peak headwater elevation at Watauga was 1963.25 feet above msl, which occurred on April 19. The peak headwater elevation in the rulebased simulation model is 1963.70 feet above msl, also occurring on April 19. This difference could increase the potential for some structures to be damaged, however, an exact number of structures is not

Table 4. Comparison of Observed Daily Average Discharge and Total Volume for Upper Holston Reservoirs with Rulebased Simulation Model Discharge and Total Volume for 1987.

DAILY AVERAGE DISCHARGE (1,000 CFS) AND TOTAL VOLUME (ACRE-FEET)								
	South Holston		Watauga		Boone		FtPatH	
Date	RiverWare	Observed	RiverWare	Observed	RiverWare	Observed	RiverWare	Observed
4/14/87	3.30	2.29	2.80	1.93	8.05	7.16	7.67	7.47
4/15/87	3.30	2.20	2.80	1.97	8.11	6.40	8.39	6.56
4/16/87	1.65	2.53	1.40	2.06	10.22	7.43	10.72	7.62
4/17/87	0.00	3.67	0.00	2.60	10.36	11.99	11.50	13.07
4/18/87	1.02	4.19	3.00	2.89	9.85	12.52	11.50	14.04
4/19/87	3.38	4.35	3.00	2.75	10.21	12.60	11.50	14.10
4/20/87	4.27	4.34	3.00	2.74	10.20	12.18	11.50	13.48
4/21/87	5.22	4.30	2.95	2.76	10.60	10.61	11.50	11.71
4/22/87	6.35	4.17	2.80	2.74	11.30	9.71	11.50	9.64
4/23/87	4.60	4.17	2.80	2.75	11.25	9.20	11.50	9.50
4/24/87	1.90	4.29	2.80	2.74	10.77	10.39	11.50	11.01
4/25/87	1.34	4.32	2.80	2.65	10.20	12.39	11.50	13.95
4/26/87	3.08	4.34	2.80	2.59	10.23	12.64	11.50	13.83
4/27/87	4.97	4.32	2.80	2.79	10.83	10.44	11.50	11.06
4/28/87	6.20	4.29	2.80	2.77	11.46	8.52	11.50	9.69
4/29/87	6.36	4.30	2.80	1.93	10.58	9.55	10.72	9.66
4/30/87	6.59	4.31	2.80	1.93	11.31	9.67	11.50	9.52
5/1/87	6.73	4.33	2.80	1.93	11.31	9.72	11.50	9.53
5/2/87	5.03	4.30	2.80	1.60	11.39	8.29	11.50	7.99
5/3/87	4.40	4.27	0.54	1.09	6.47	6.41	6.55	7.94
5/4/87	4.40	4.32	0.54	1.27	6.57	8.91	6.79	9.23
5/5/87	4.40	3.88	1.03	2.61	6.52	7.39	6.62	6.56
5/6/87	3.30	3.20	0.45	1.99	4.88	6.64	5.02	6.40
5/7/87	3.30	3.20	0.46	1.93	4.99	5.73	5.29	6.55
5/8/87	3.30	3.20	0.47	1.91	4.90	6.33	5.16	6.80
Total	98.39	97.08	53.24	56.92	232.56	232.82	245.43	246.91
Total acre-feet	195,200	192,500	105,600	112,900	461,300	461,800	486,800	489,700

available. For South Holston reservoir, the study shows that there are approximately 71 structures surrounding the reservoir that may potentially be damaged by headwater elevations at or below 1735 feet above msl. This number stays constant until the headwater elevation reaches 1740 feet above msl when it jumps to 103 structures. The actual peak headwater elevation at South Holston of 1736.92 feet above msl occurred on April 26. The peak headwater elevation in the rulebased simulation model is 1739.19 feet above msl, occurring on April 27. Since there are no structures located between elevations 1735 and 1740 feet above msl, there is no potential for additional flood damage.

Structures that have the potential to incur damage at these elevations include some mobile homes, but primarily are marina facilities such as docks, shops, and restroom buildings. Most structures and infrastructure located on land surrounding these reservoirs is required to be sited above the maximum probable elevation at each reservoir, which is 1980 feet above msl at Watauga and 1747 feet above msl at South Holston.

Again, a note regarding a comparison between actual reservoir operations during the 1987 flood and rulebased simulation model results is that, as stated previously, the rulebased simulation model does not take into consideration events occurring within other areas of the Tennessee Valley. Any operational decisions made at the time reflect the goal of providing flood protection not only to local areas, but to the entire Tennessee Valley, to the extent possible. Therefore, any comparison is not an attempt to second

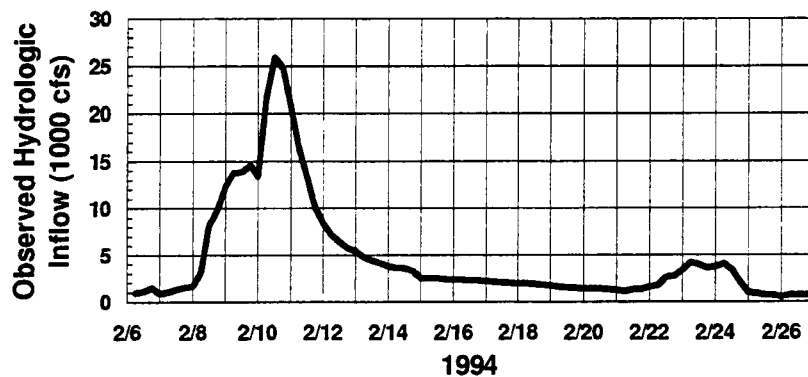
guess decisions made during actual operations. It is simply a mechanism used to determine the suitability of this software as a tool for future flood studies.

February 1994: Actual Reservoir Operations

During February 1994, a large storm deposited over five inches of rain across the Upper Holston watershed. This rainfall occurred on February 9-12. The resulting inflow hydrographs can be seen in Figure 30. At the beginning of the storm, headwater elevations were above the minimum levels that had been established as part of the 1990 EIS, Tennessee River and Reservoir System Operation and Planning Review, but they were below flood guides. As a result of the four days of rainfall, headwater elevations rose over seventeen feet at South Holston and over eight feet at Watauga. The headwater elevation at both South Holston and Watauga remained above their respective flood guides for the remainder of the month. The headwater elevation at Boone rose about fifteen feet, and discharges from Fort Patrick Henry exceeded 11,500 cfs. Although the elevation at Boone rose to such a high level, it was quickly brought back to within the daily operating range by discharging more than 12,000 cfs. The sluiceway was used to evacuate water from South Holston reservoir with a total discharge of about 4,500 cfs. Discharges did not exceed turbine capacity at Watauga dam.

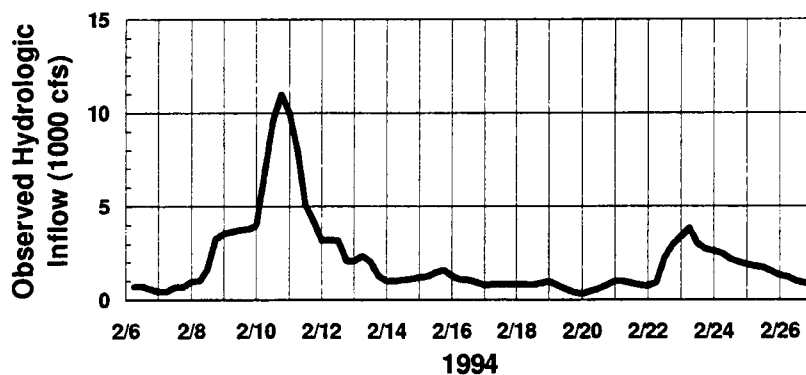
Although the headwater elevation at South Holston, Watauga, and Boone dams rose dramatically as a result of this storm event, these elevations did not exceed the levels of the normal summer operating range at any of the reservoirs. The top of the normal summer operating range is 1729 feet above msl at South Holston, 1959 feet above msl at

SOUTH HOLSTON RESERVOIR



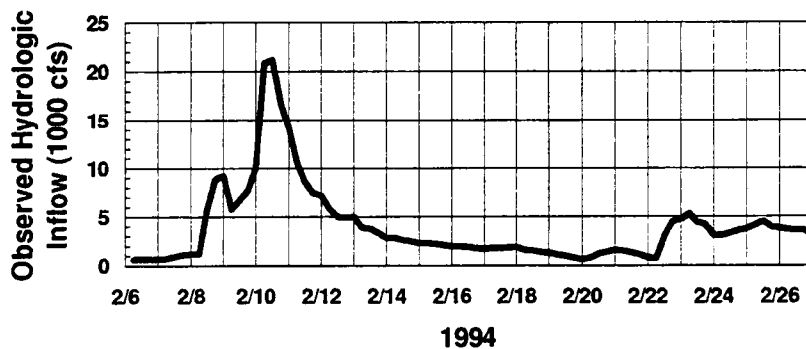
a) Hydrologic Inflow into South Holston Reservoir in February 1994.

WATAUGA RESERVOIR



b) Hydrologic Inflow into Watauga Reservoir in February 1994.

BOONE RESERVOIR



c) Hydrologic Inflow into Boone Reservoir in February 1994.

Figure 30. Hydrologic Inflow Hydrographs from Storms Occurring in February 1994.

Watauga, and 1383 feet above msl at Boone. These elevations correspond to the flood guides at South Holston and Watauga and the top of daily operating zone at Boone.

However, these elevations were extremely high for this time of year. At South Holston and Watauga, where headwater elevations remained above their respective flood guides for the remainder of the month, a dangerous situation could have arisen had another large rainfall event occurred. This is because the headwater elevations within these reservoirs remained above levels that had been determined when the reservoirs were constructed to allow adequate storage space for runoff.

February 1994: RiverWare Rulebased Simulation Reservoir Operations

The rulebased simulation model, using the Upper Holston ruleset, during February 1994 once again closely parallels actual reservoir operations. A comparison of actual headwater elevations with modeled values for South Holston, Watauga, and Boone reservoirs shows that the same pattern is followed at all three projects except that the modeled headwater elevations are all lower than observed values during the flood event (Figures 31, 32, 33). The primary difference between model results and actual operations is that discharges from Fort Patrick Henry dam are increased to turbine capacity well in advance of the rainfall in the model. Also, spillway discharge is initiated more than one day earlier in the modeled results than in actual operations (Figure 34). Although the spillway is utilized more quickly in the model, the discharge does not exceed 11,500 cfs, which is the critical flow for the city of Kingsport. Above this discharge, there is a potential for flood damage to be incurred.

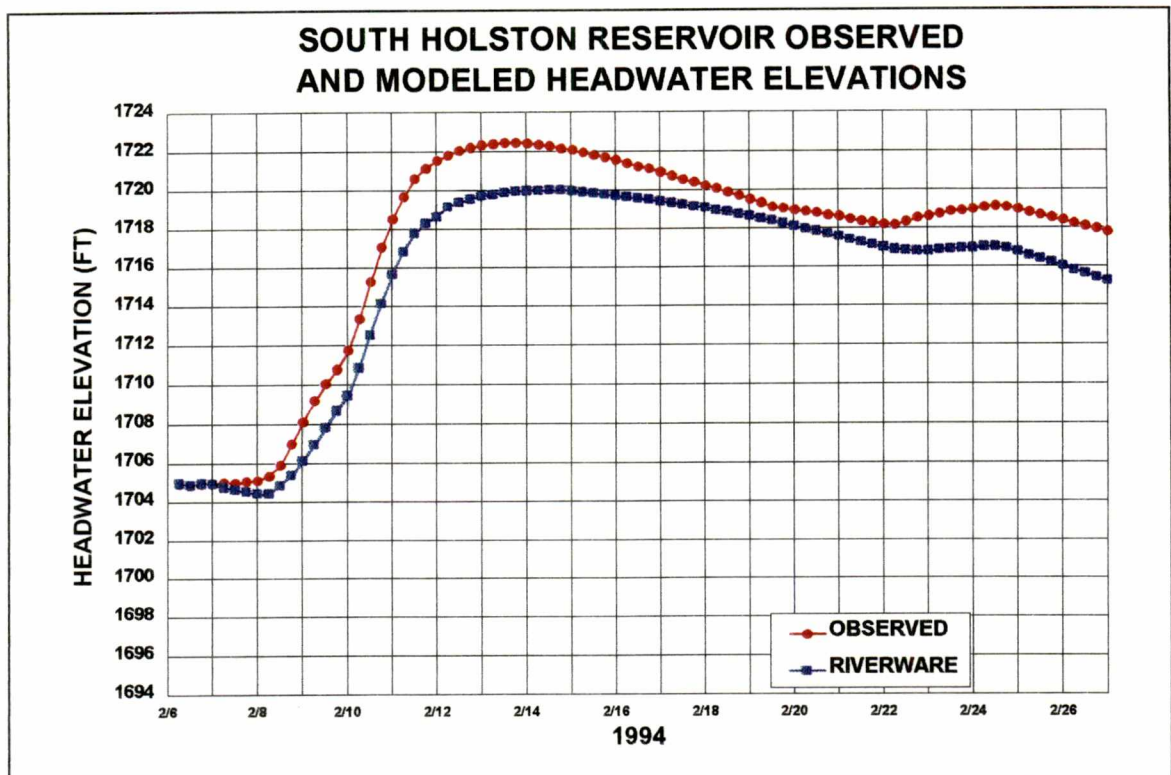


Figure 31. 1994 Observed and Modeled Headwater Elevations at South Holston Dam.

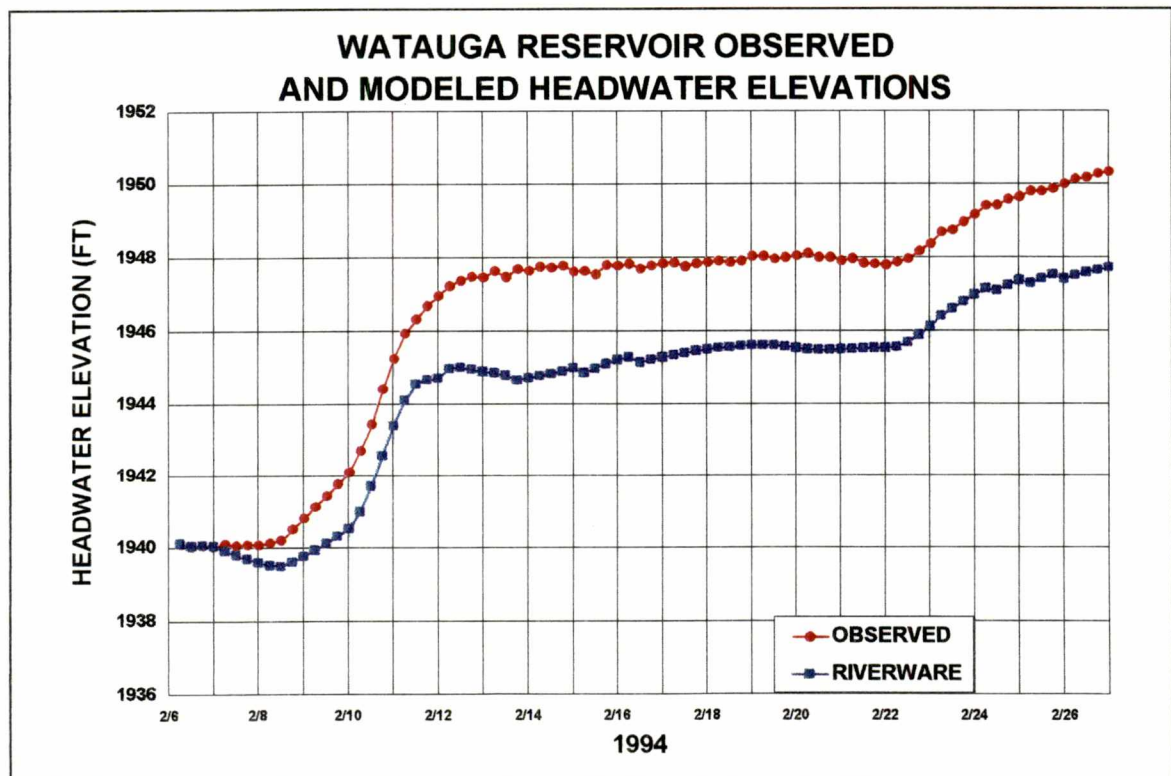


Figure 32. 1994 Observed and Modeled Headwater Elevations at Watauga Dam.

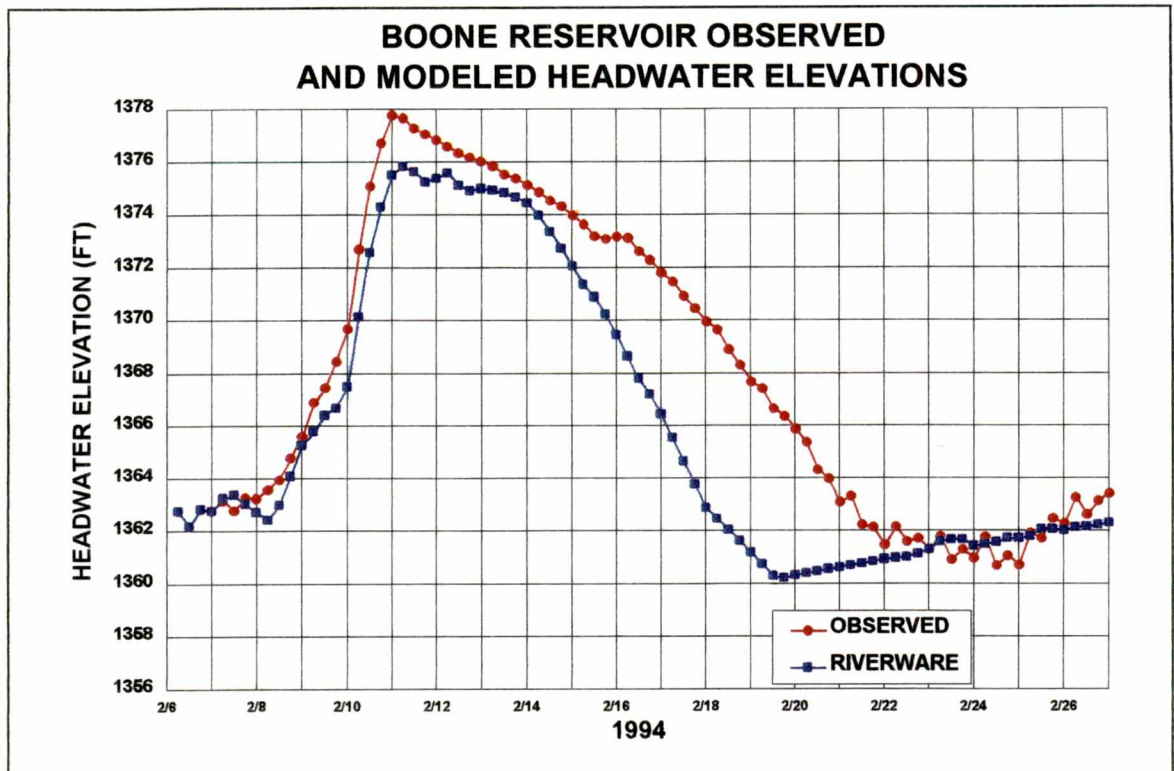


Figure 33. 1994 Observed and Modeled Headwater Elevations at Boone Dam.

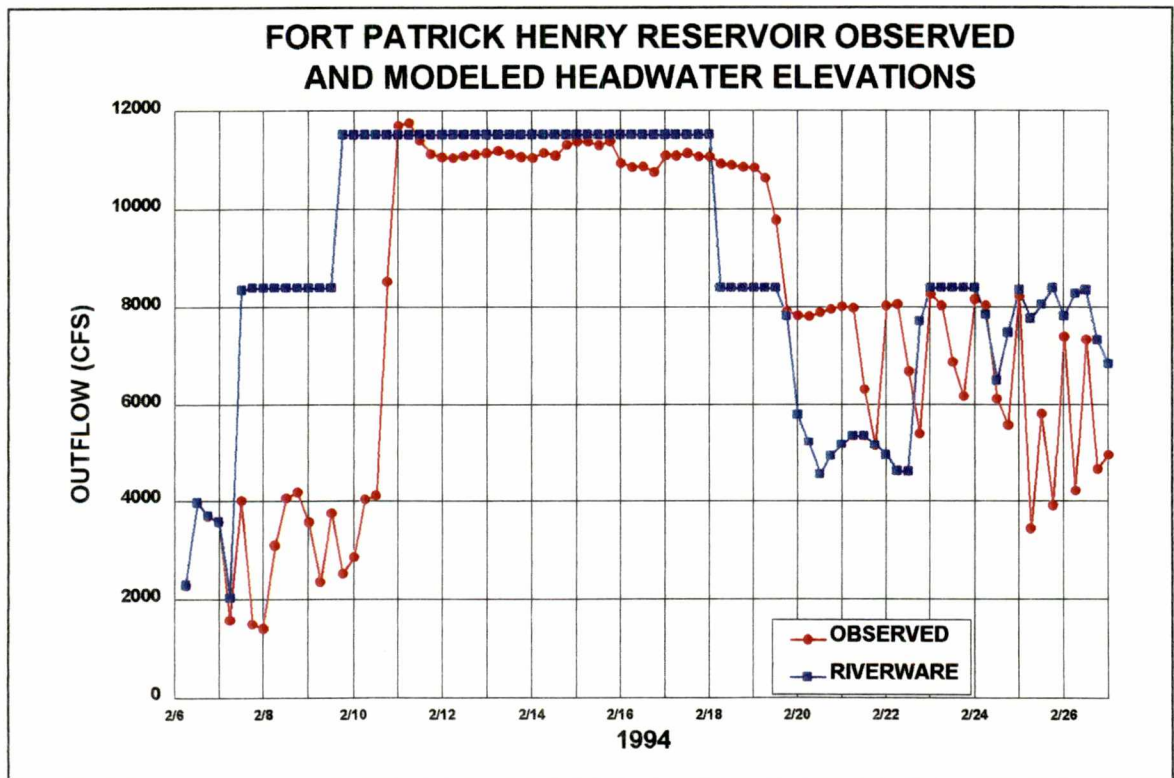


Figure 34. 1994 Observed and Modeled Discharges from Fort Patrick Henry Dam.

The increase in discharge within the rulebased simulation model over the observed discharge from Fort Patrick Henry dam prior to the storm event allows more water to be released from the upstream projects, South Holston, Watauga, and Boone, resulting in lower headwater elevations. For example, almost 123,000 acre-feet of water was released from South Holston dam during the twenty day time period in the rulebased simulation model as opposed to the actual amount of 114,000 acre-feet. For Watauga, 41,500 acre-feet was released in the rulebased simulation model and 26,200 acre-feet of water was actually released. Also, over 335,000 acre-feet of water was discharged from Boone dam over the twenty day time period being studied in the rulebased simulation model as compared to the actual amount of just over 294,000 acre-feet (Table 5). This results in a two foot reduction in peak headwater elevation at South Holston, Watauga, and Boone dams.

Although the peak elevations at South Holston, Watauga, and Boone dams were reduced in the rulebased simulation model, the headwater elevations still reached very high levels. The headwater elevation remained above the flood guide at South Holston dam, just as it did in reality. At Watauga, the headwater elevation was slightly above the flood guide during the peak of the storm and slightly below the flood guide at the end of the model time period. The headwater elevation at Boone dam rose above the top of the daily operating zone, but ended the model time period near the bottom of the daily operating zone.

Table 5. Comparison of Observed Daily Average Discharge and Total Volume for Upper Holston Reservoirs with Rulebased Simulation Model Discharge and Total Volume for 1994.

DAILY AVERAGE DISCHARGE (1,000 CFS) AND TOTAL VOLUME (ACRE-FEET)								
	South Holston		Watauga		Boone		FtPatH	
Date	RiverWare	Observed	RiverWare	Observed	RiverWare	Observed	RiverWare	Observed
2/8/94	3.00	0.83	1.98	0.59	8.02	1.86	6.79	2.12
2/9/94	3.00	0.36	1.88	0.24	7.44	3.83	8.39	3.72
2/10/94	3.15	0.30	1.62	0.17	9.03	1.80	9.94	2.87
2/11/94	2.48	0.11	1.08	0.24	9.56	4.42	11.50	7.09
2/12/94	1.65	1.30	1.4	0.11	10.29	11.06	11.50	11.32
2/13/94	2.48	3.34	2.1	1.16	10.50	10.15	11.50	11.08
2/14/94	3.30	3.94	2.19	1.16	10.57	10.21	11.50	11.09
2/15/94	3.30	4.49	0.3	1.17	10.63	10.38	11.50	11.22
2/16/94	3.30	4.49	0.78	1.16	10.67	9.34	11.50	11.23
2/17/94	3.30	4.48	0.77	0.77	10.75	9.77	11.50	10.88
2/18/94	3.30	4.46	0.16	0.75	10.60	10.25	11.50	11.08
2/19/94	3.30	4.49	0.56	0.40	7.64	10.00	8.39	10.86
2/20/94	3.30	3.46	0.77	0.40	6.11	8.20	7.59	9.03
2/21/94	3.30	2.73	0.83	1.18	4.99	8.89	4.96	7.91
2/22/94	3.30	2.67	0.77	1.17	4.90	7.47	5.20	6.87
2/23/94	3.30	1.13	0.66	0.67	6.79	5.83	6.33	7.10
2/24/94	3.30	2.56	0.54	0.69	8.08	7.96	8.39	7.31
2/25/94	3.30	3.58	0.98	0.69	7.43	7.16	7.53	6.99
2/26/94	3.30	4.47	1.49	0.40	7.89	5.05	8.00	5.14
2/27/94	3.30	4.48	0.08	0.10	7.18	4.77	7.69	5.28
Total	61.96	57.67	20.94	13.22	169.07	148.40	181.20	160.19
Total acre-feet	122,900	114,400	41,500	26,200	335,300	294,300	359,400	317,700

Even though the scenario generated by the Upper Holston ruleset appears to be a better operation of the Upper Holston system than the actual operation, this ruleset does not take into account conditions in other areas of the Tennessee Valley. This was a storm that covered much of the Tennessee watershed, and discharges from reservoirs in the Upper Holston system were coordinated with discharges from all of the reservoirs in the Tennessee system to reduce flooding potential to the extent possible in all areas of the Valley. Once again, the objective of a comparison is not to second guess any decisions made at the time, but to evaluate the suitability of this software as a tool for future flood studies.

VIII. Conclusions

The objective of this thesis was to evaluate RiverWare rulebased simulation as a tool in a flood risk study. This evaluation was completed by addressing each of the three questions presented at the beginning of this investigation. Based on discussions of the answers to each of the three questions, a conclusion can be drawn as to whether or not RiverWare rulebased simulation is a tool that should be used in future flood risk studies. These questions are: Can rules be written that drive a model to operate a reservoir system in a manner reflective of actual operations? Is this tool easily adaptable to changes in operating policy? Does rulebased simulation help reservoir operators make decisions that could impact current and future operations?

Although RiverWare rulebased simulation was tested using three actual storms in the Upper Holston watershed, modeled operations were not expected to exactly imitate observed operations, because many changes in operating policy and improvements in modeling capability have occurred over time. Additionally, although weather predictions and, therefore, inflow forecasting have improved over time, there is still a great deal of uncertainty in this aspect of reservoir operations. For this reason, it is necessary for reservoir operators to be prepared for a range of possible conditions. This preparation can be accomplished by utilizing RiverWare rulebased simulation in flood risk studies. Various modeling scenarios that are all governed by the same operating constraints can be evaluated in advance of a predicted high flow event.

By comparing observed reservoir conditions in the three storm events discussed in the previous section with model results, a conclusion can be made that this

tool allows rules to be written which produce results reflective of actual operations. If a ruleset could not be written that reflects actual operating scenarios, there would be no cause for further development of this software as a tool in flood risk studies. Although RiverWare rulebased simulation model results and actual reservoir operations are not identical, a ruleset was written that produces reasonable operating scenarios that reflect the constraints placed on the system at the current time. With this in mind, reservoir operators should use RiverWare rulebased simulation as an aid in the decision making process. RiverWare rulebased simulation, as with any software used by reservoir operators, is a tool, with the final decisions on how to operate the reservoir system being made by the engineer. However, RiverWare rulebased simulation does allow the operator to quickly and easily realize the consequences of various operating scenarios so that decisions can be made based on model results.

The ability to quickly and easily modify rules to reflect changes in operating policy makes RiverWare a tool that could be very valuable in flood risk studies. Both written operating policies and unwritten "rules-of-thumb" applied to reservoirs in the TVA system are dynamic, with changes occurring from time to time. An example of a recent change is the establishment of minimum operation guides (MOGs) on many of the tributary reservoirs. Rulebased simulation was designed to be used by the engineers who will be operating a reservoir system without necessarily having to rely on a programmer to make model changes. The rule palette is intended to allow the user to write and modify rules without knowledge of tcl (tool command language) or any other programming language. Rules can be easily added, removed, or modified through the

rule palette as operating constraints change. Operating rules are not hard coded within the model, thereby allowing easy adaptation to changes in operating policy.

RiverWare rulebased simulation does have the potential to help reservoir operators make decisions that could influence current and future operations. For example, this software tool could be used in long term planning studies where rulebased simulation model runs are completed for weeks, months, or even years into the horizon. These models can be run based on rules rather than interactive user input. For current operations, the user can explore various conditions using the same ruleset. For example, the impact of a 7-inch rain versus a 1-inch rain can easily be determined. The operator could have all of this information available which would allow much greater preparation in advance of a storm event.

In conclusion, RiverWare rulebased simulation is a modeling tool that has the potential to be very meaningful in flood risk studies. However, much work remains to be completed before any implications to reservoir operations can be determined. Rulebased simulation has thus far been applied to only one subsystem of the large Tennessee Valley reservoir system. The goal of the flood risk analysis study that will be conducted on the TVA system is to maximize hydropower while still meeting other operational objectives such as flood control, navigation, and recreation. Any enhancements to operation of the TVA system will emerge as a result of this study. RiverWare rulebased simulation is a modeling tool that will be a very valuable part of this investigation. Therefore, RiverWare rulebased simulation should be broadened to include the entire TVA system

as well as given consideration for expansion into other types of reservoir planning investigations.

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Appendix

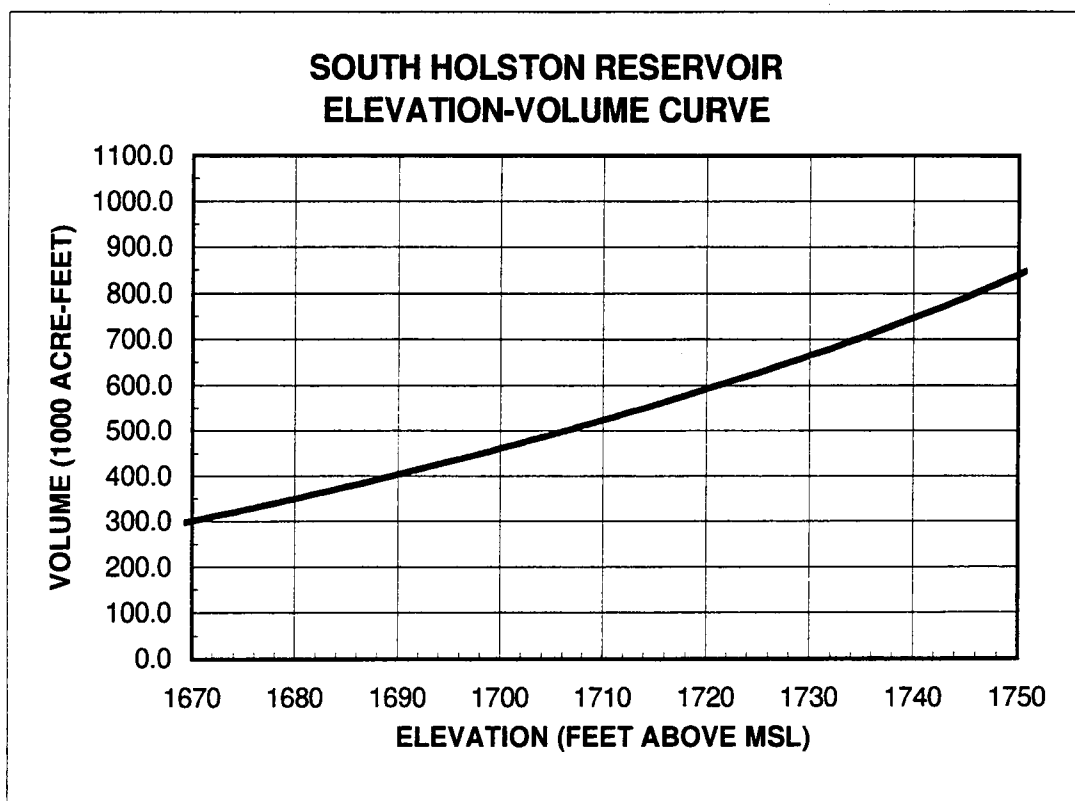


Figure 35. Elevation-Volume Curve for South Holston Reservoir.

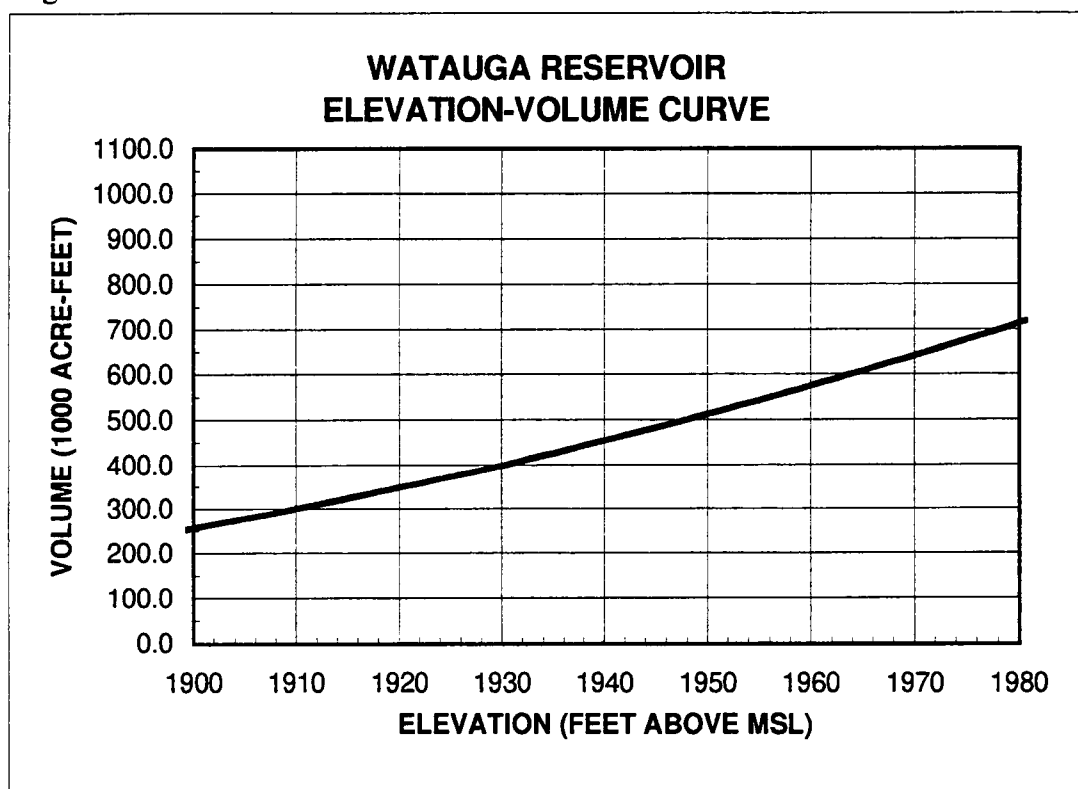


Figure 36. Elevation-Volume Curve for Watauga Reservoir.

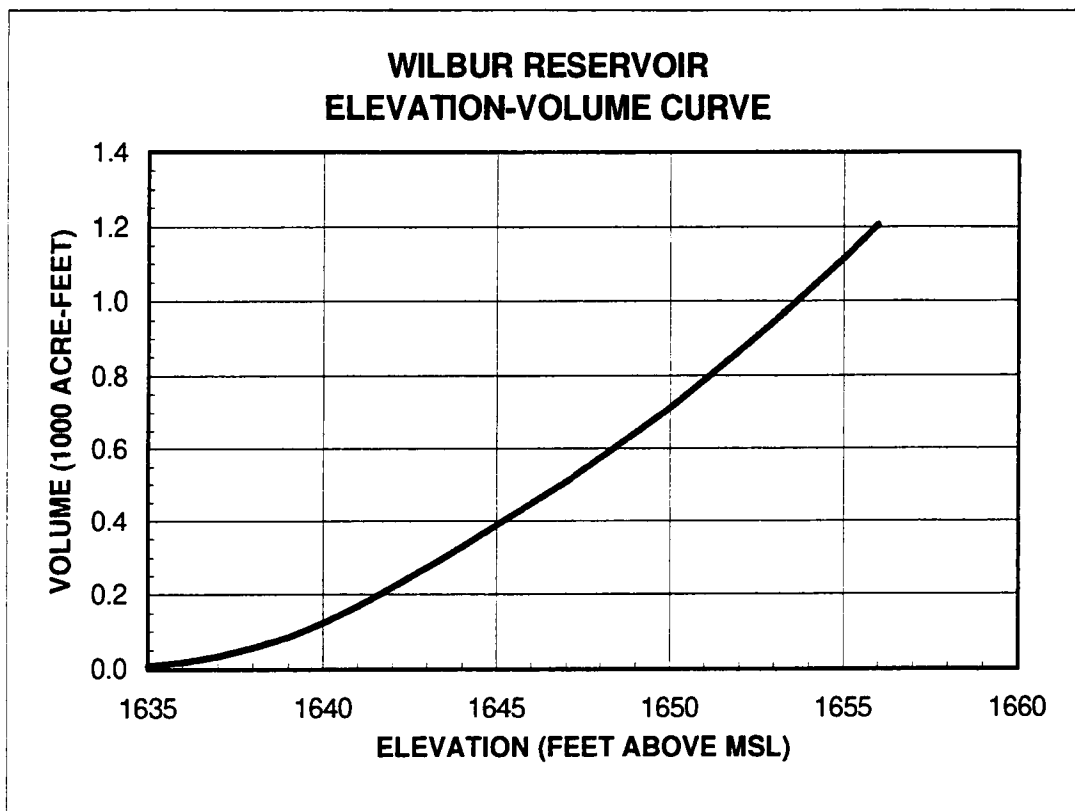


Figure 37. Elevation-Volume Curve for Wilbur Reservoir.

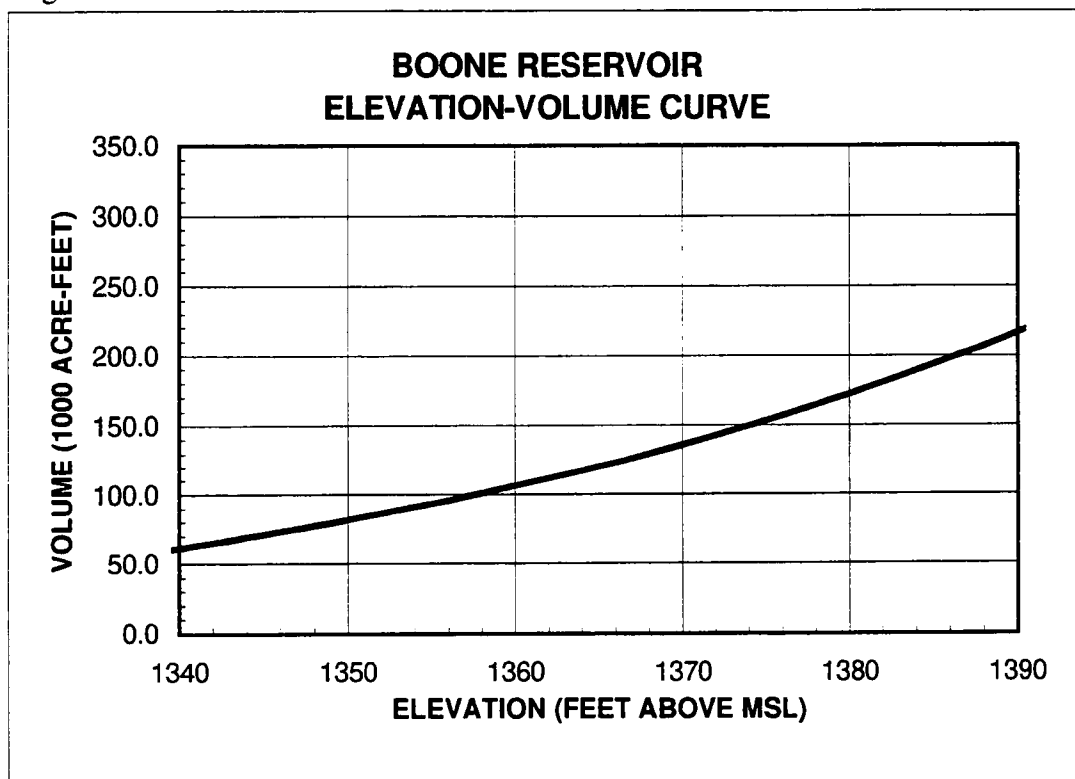


Figure 38. Elevation-Volume Curve for Boone Reservoir.

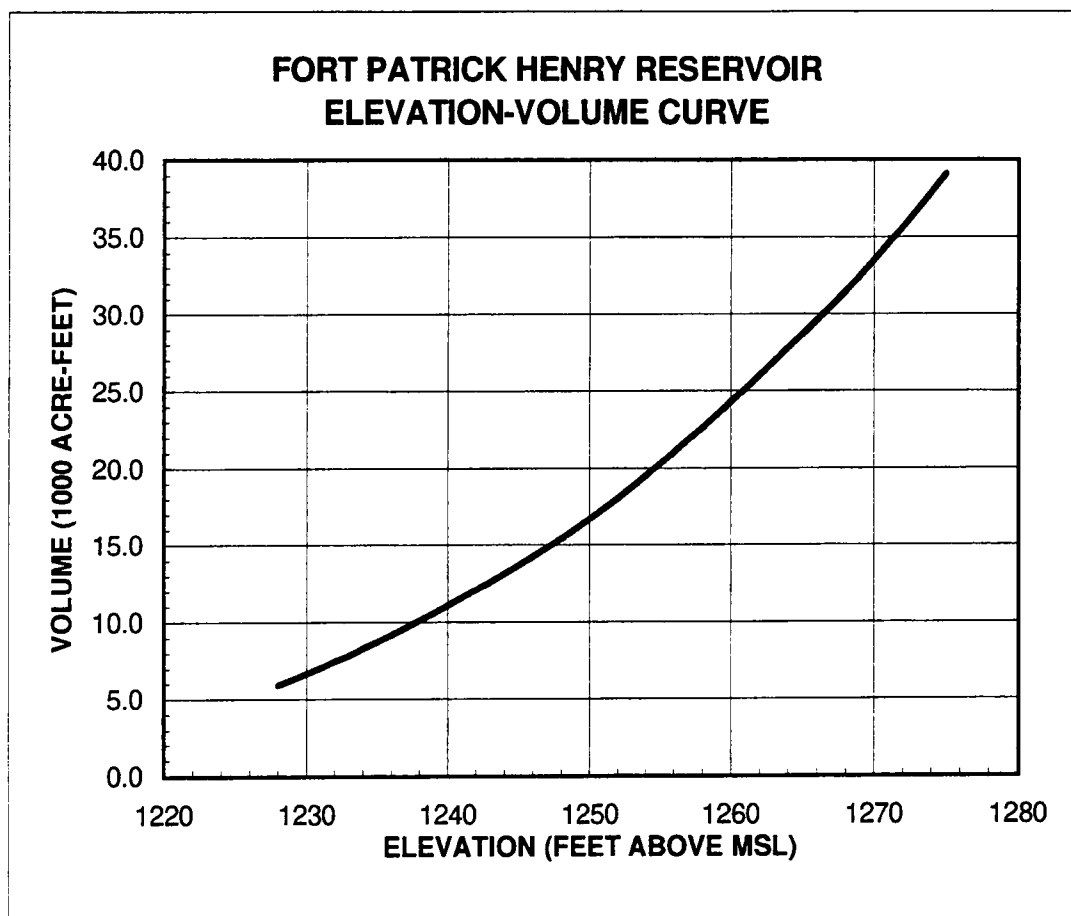


Figure 39. Elevation-Volume Curve for Fort Patrick Henry Reservoir.

Vita

Patricia Suzanne Hardy was born in Atlanta, Georgia in 1971. She lived in Riverdale, Georgia where she graduated from North Clayton Senior High School in 1989. Upon completion of high school, she began undergraduate studies at the Georgia Institute of Technology. There she majored in Civil Engineering and worked as a cooperative education student for the U.S. Geological Survey, Water Resources Division. She received a Bachelor of Civil Engineering degree in 1995 from Georgia Tech and began her engineering career at the Tennessee Valley Authority where she is currently employed in Water Management. She began a Master's degree program in Environmental Engineering at the University of Tennessee in 1996.