University of Washington
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AN INTERACTIVE SIMULATION MODEL FOR THE CEDAR/TOLT WATER SUPPLY SYSTEM

Karol A. Erickson
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Water Resources Series
Technical Report No. 73
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Abstract

From a water supply standpoint, the performance of a water resource system under drought conditions is the limiting consideration for both operation and design. In operating a water supply system, the ability to forecast inflows, and to take timely action to control demand is crucial to avoid unplanned supply shortfalls under critical streamflow conditions. Interactive simulation represents a useful tool to effect drought management strategies. In this work, an interactive simulation model of the Seattle water supply system was developed, that allows user interaction on a weekly time step in response to projected deficits from streamflow forecasts of length one, four, twelve, and sixteen weeks. Upper and lower forecasts are also predicted, based on forecast error statistics. If water supply deficits are predicted to occur under the lower forecast during the succeeding twelve weeks, user interaction is allowed to reduce demand and/or to adjust instream flow requirements. Thus, the user is allowed to specify the timing and severity of management options and to evaluate the consequences of alternative strategies.

The model may also be run in batch mode to estimate the yield associated with various expansion options. In this mode, computations are performed to automate reduction of instream flow requirements under critical streamflow conditions. Summary statistics for length and severity of supply shortfalls over the record length are provided.

Important conclusions of this study are 1) the yield of the existing system is considerably higher than has been previously estimated using monthly inflows. This is partly so because the added flexibility of weekly operation allows reduction of instream flow requirements to critical levels more quickly under extreme situations, 2) with additional storage in the Cedar basin associated with the so-called City Light Plan, and installation of a diversion structure on the North Fork of the Tolt River, the system can reliably deliver the projected year 2025 demand, and 3) the most attractive feature of the simulation model is its potential for use in negotiation of instream flow requirements with fisheries managers in real time.

Acknowledgments

The work reported herein represents the Masters thesis of the first author. Funding for the project was provided by the Seattle Water Department, with William Mancinelli as project officer. Water Department assistance in acquisition of data for estimation of historic weekly streamflow sequences was provided by Tom Johansen. The authors are especially grateful to James Mock of the University of Washington College of Engineering, and to the University of Washington Acedemic Computer Center, for making available its VAX 11/780 for this project. The authors also appreciate the prompt and accurate typing of Louise Colbourn.

TABLE OF CONTENTS

LIST OF FIGURES

LIST OF TABLES

Chapter 1

INTRODUCTION

Efficient management of water resources is becoming an increasingly important concern as competition for existing water supplies increases. Many reservoirs originally designed for water supply only are now expected also to provide hydropower generation, fisheries mainentance, recreational facilities, and flood protection. When demands are small relative to supplies, reservoir management is not a difficult problem. During low flow periods, however, reservoir management can become a complex problem, as many demands compete for a limited supply.

The objective of a reservoir management policy during drought conditions is two-fold: 1) to distribute the available water among the various users according to the priorities defined by the system, and 2) to minimize the severity of the shortages if all demands cannot be met. Because economic losses due to water shortages are most often nonlinear, minimizing losses is accomplished by distributing the shortages over time. Drought management strategies, therefore, usually consist of a hierarchy of water-use reductions, with increasingly large demand restrictions imposed as the drought severity increases.

Decisions on the timing and extent of demand restrictions are complicated by the random nature of streamflows. Ideally, an appropriate management policy would be based on the risk associated with various projected deficits. Because of the complex nature of many water supply systems, however, explicit deficit risk assessment is often difficult. A computer model is a useful tool for showing the deficit risks associated with alternative operating policies. The following section summarizes some of the models that have been developed to assist in reservoir management.

MODELING APPROACHES

Numerous approaches to modeling water resource systems have been developed in recent years to identify and evaluate operating policies for multi-purpose reservoir systems. Modeling approaches can be classified as either simulation or optimization, and the nature of the streamflows used in the model can be described as either deterministic or stochastic. From this viewpoint, the four possible types of models are deterministric optimization, stochastic optimization, deterministic simulation, and stochastic simulation.

Optimization: Optimization models are designed to determine the "best" solution to a problem subject to a set of constraints. The two optimization techniques most often used are linear and dynamic programming. Linear programming is the most often used optimization technique. Linear programming requires that all elements of the system be represented as linear functions; this restriction can limit its accuracy and applicability. A large advantage of linear programming, however, is that it identifies the binding constraints and their marginal costs with respect to the system objective. Dynamic programming allows non-linear functions, but is, in general, more computationally intensive, which can limit its use for multi-reservoir applications. Dynamic programming has the further disadvantage of being a general framework rather than a specific computational technique. Therefore, while it is very flexible, each problem solution method is unique. In addition, inflows and storages must be discretized for dynamic programs, resulting in approximate solutions (Klemes, 1979). Difficulties with optimization models in general arise when the objective of the system is difficult to define. This occurs when the system objective is some combination of inconsistent units (and trade-offs are poorly defined), or if the objective is a function of political negotiations.

The way in which streamflow data is incorporated into the optimization model determines whether the model is classified as a deterministic or stochastic model. Deterministic Optimization models use historic streamflows to determine a set of operating rules that are optimum for the historical record. These rules are then assumed to be near optimum for future conditions. Stochastic Optimization models incorporate the random nature of streamflows. Stochastic linear programs are generally of two types:

1) The chance-constraint approach, developed by Revelle, et al. (1969), and extended by Houck and Datta (1981) assumes streamflow events of a specified probability occur each time period. For example, assuming a 100-year streamflow record and a desired probability level of 10 percent, the 10th lowest streamflow from the historic record for each time period would be used to drive the model. Because the probability of each of these streamflows occurring consecutively is usually quite low, this method underestimates the system yield.

2) Two-stage linear programming, described in Loucks, et al. (1981), uses a different approach to incorporate the probabilistic nature of streamflow. The probability distribution of the streamflow is approximated by a discrete distribution, generally of three to ten values. The basic constraint set is then repeated for each possible value of streamflow. This can cause the program to be quite large and significantly more expensive to develop and solve.

Stochastic dynamic programming requires the addition of transition probabilities between consecutive states in the model. This is usually not conceptually difficult to incorporate into a dynamic program, however, it leads to extreme dimensionality problems. Examples of stochastic optimization models include Buras (1966), Butcher (1971), and Roefs and Guitron (1975).

Simulation: Simulation models, in contrast to optimization models, do not search for an optimal operating policy, but instead describe the system response to a specific set of inputs for a given operating policy. Simulation can be used to evaluate or compare several alternative operating policies, or system configurations. Because it can incorporate non-linearities and need not discretize storage or inflow, it can provide more accurate descriptions of system response than can optimization models. Use of a simulation model is appropriate when the number of possible policies are relatively few in number, either because they have been previously identified by an optimization model, or because of inherent physical or institutional limitations on the system. The relative merits of optimization and simulation models compliment each other when an optimization model is used as a screening tool and the results are verified and refined using a simulation model.

Deterministic simulation uses the historic streamflow record to drive the model. Described in Maass et al. (1962) deterministic simulation modeling has been employed in a wide variety of reservoir applications, such as Hufschmidt and Fiering (1966), Askew, et al. (1971), and Liu, et al. (1972). Stochastic simulation usually consists of driving the model with several synthetically generated streamflow sequences (see Jackson (1975) for a review of streamflow generating techniques). As an example of this approach, Hirsch (1981) combined a stochastic streamflow generator with a simple simulation model to give conditional probabilities of future reservoir storage volumes. Stochasticity need not be limited to inflows, however; demands and other model elements can also be represented stochastically in simulation models.

Interactive Simulation: Interactive simulation is a variation of the simulation approach that allows the user to modify system operating policies during the course of a modeling run and, therefore, to compare the effects of various strategies directly. Interactive models can be a valuable tool to assist communication between system analysts and managers if the model is designed for use by non-technical decision-makers. Results are immediate and usually in a graphical or tabular form that is relatively easy to interpret. Interactive capability facilitates understanding model complexities and non-intuitive relationships. Interactive models have begun to gain acceptance in water resources planning, as evidenced by Palmer, et al. (1980), which describes an interactive model designed to be used as a negotiation aid for defining release policies among competing agencies. French, et al. (1980) describe an interactive simulation package with extensive graphics capability. Neither of these models, however, explicitly incorporate reliability indicators, an important concern for water supply systems.

PURPOSE OF STUDY

The purpose of this study is to develop an interactive simulation model for drought management that includes explicit probability estimates of future events. The model was developed specifically for the Seattle water supply system which serves approximately one million domestic, commercial, and industrial users in the metropolitan Seattle area. Because previous work has been directed at this system, including a detailed simulation model by Draper, et al. (1981), streamflow forecasting by Lettenmaier, et al. (1980), and a linear programming model by the URS Co. (1981), the purpose of the study is to combine results of the earlier work into a flexible interactive simulation model that can be incorporated into the management process.

The remainder of this report is organized as follows: The Seattle water supply system is described in Chapter 2, and the interactive simulation model is described in Chapter 3. Chapter 4 describes the streamflow forecasting methods used by the model. Chapter 5 provides examples of selected interactive sessions and presents results of several yield determinations. Chapter 6 presents a summary, conclusions, and recommendations for future study.

Chapter 2

DESCRIPTION OF THE SEATTLE WATER SUPPLY SYSTEM

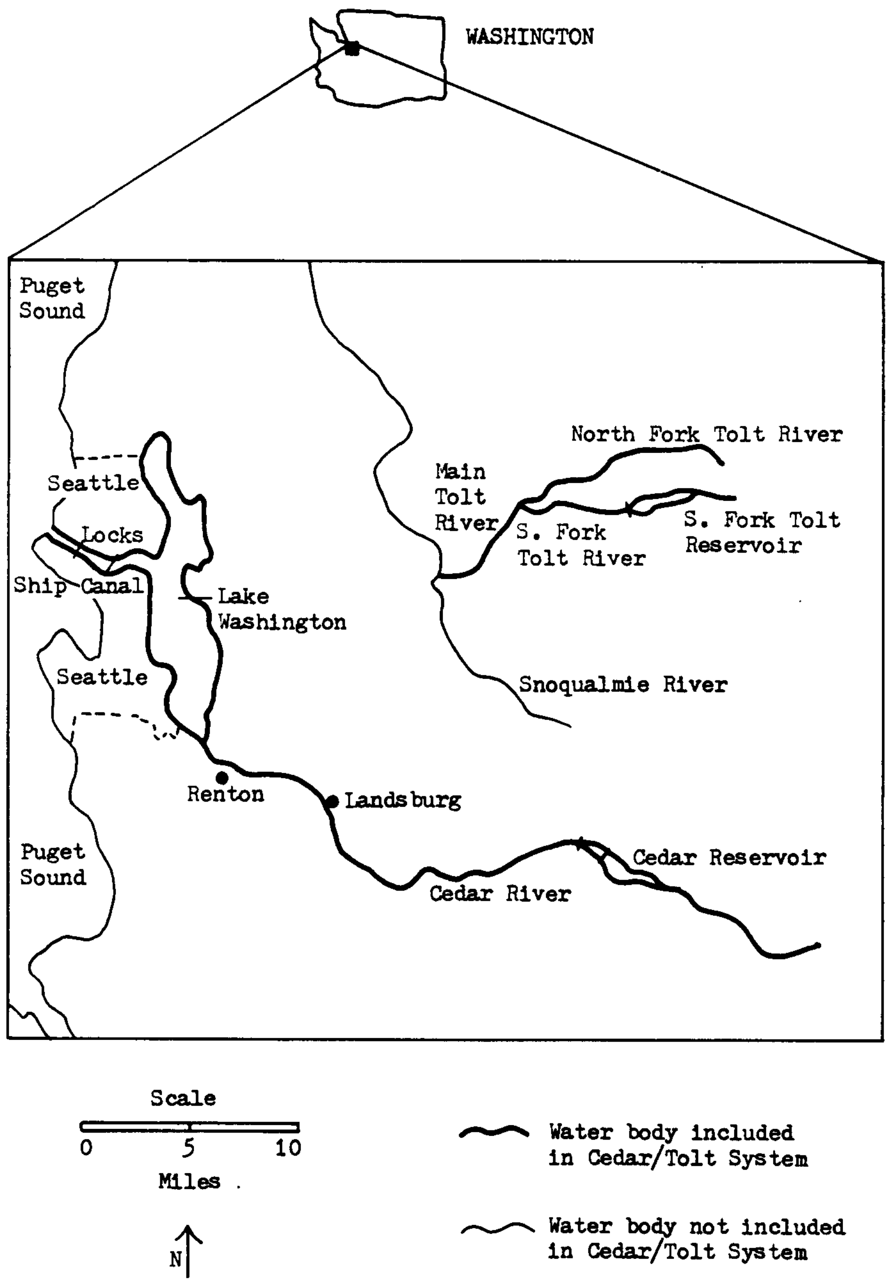
SETTING

Seattle obtains its municipal and industrial water supply from the Cedar and Tolt watersheds (Figure 1). The Cedar and Tolt rivers drain west Cascade basins of approximately 190 and 50 square miles, respectively. Elevations range from 15 to 5400 feet in the Cedar, and 600 to 5900 feet in the Tolt. Precipitation varies with elevation, ranging from 35 inches to over 200 inches annually. Snow can accumulate to over 500 inches annually at the highest elevations, and usually persists until June. The highest instantaneous streamflows occur from November through January, although the largest monthly volumes occur during the peak snowmelt season, April and May. Lowest streamflows occur from July through September and can occasionally extend into early winter.

GENERAL CHARACTERISTICS

The Cedar/Tolt Water Supply System represents a complex, multi-purpose reservoir system, with many potentially conflicting water uses. The primary purpose of the system is to provide municipal and industrial water to the approximately one million residents of the Seattle metropolitan area. Water stored in the Cedar reservoir also generates up to 30 megawatts of electricity for the region. In addition, the Cedar River is the site of the largest sockeye salmon run in the continental U.S. Although not designed for this purpose, the Cedar reservoir assists in maintaining the salmon population by controlling

Figure 1.
Cedar/Tolt Water Supply System: Location



floods in the winter and maintaining summer and fall flows greater than those that would naturally occur. The Cedar River also provides high-quality water to Lake Washington, a large freshwater lake within the Seattle metropolitan area.

PHYSICAL CHARACTERISTICS

The Cedar/Tolt system, shown schematically in Figure 2, includes reservoirs on the Cedar and South Fork Tolt rivers, and diversion sites on the Cedar at Landsburg and on the South Fork of the Tolt River downstream of the reservoir. Water is piped from the diversion sites to the Seattle Water Department distribution system. Both reservoirs serve primarily to store snowmelt runoff for supplementing summer low flows. The ratio of active storage capacity to mean annual flow is quite small for both reservoirs: 0.09 for the Cedar and 0.45 for the Tolt. Summaries of flow characteristics and reservoir sizes are given in Table 1. Active storage in the two reservoirs is sufficient for approximately 2 months of municipal and industrial demand during the summer months at the current demand level if all other demands are satisfied. The lowest storage volumes generally occur during the late summer and fall.

The Cedar reservoir system is composed of two dams as shown in Figure 3. Upstream is a low dam constructed of timber, known as the crib dam, that controls the elevation of Chester Morse Lake. The total storage capacity of Chester Morse Lake is 55,000 Acre-Feet (AF), of which only 19,000 AF is useable at the present time because of the large volume of dead storage. Approximately 1.4 miles downstream is a higher masonry dam creating what is

Figure 2.

Cedar/Tolt Water Supply System:
Schematic Representation

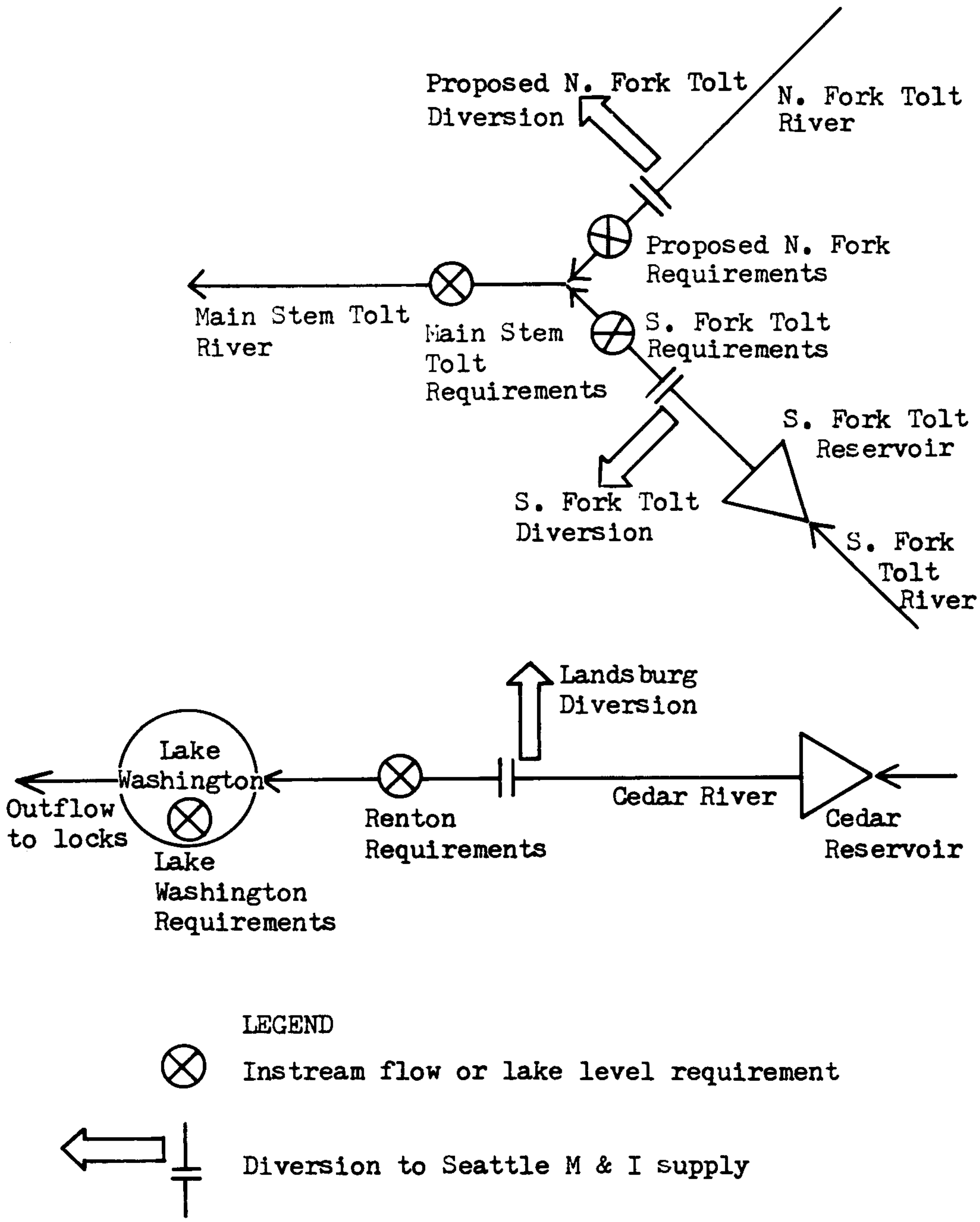


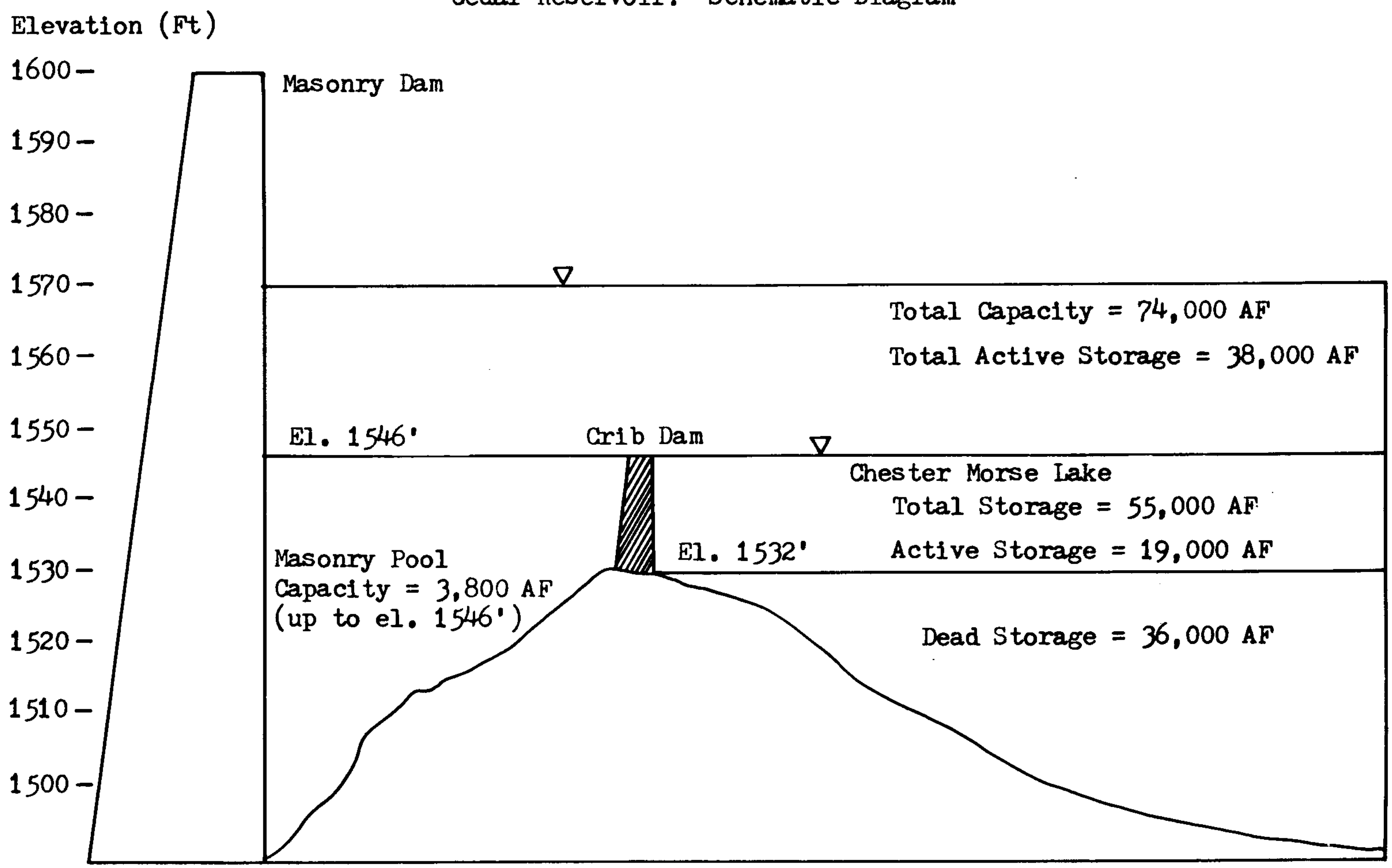
TABLE 1

Reservoir Capacities and Average Inflows

	Cedar	Tolt
Average Annual Inflow (Acre-Ft)	415,000	126,000
Total Reservoir Capacity (Acre-Ft)	75,200	57,000
Maximum Active Storage[1]	38,400	56,000
Ratio of Active Storage to Average Annual Inflow	0.09	0.45

[1]Active Storage = Total Storage -Flood Storage -Dead Storage

Figure 3.
Cedar Reservoir: Schematic Diagram



called the masonry pool. The total storage capacity resulting from this dam is theoretically 154,800 AF. Severe seepage losses from the masonry pool, however, occur when the water depth exceeds 30 feet, limiting the total storage capacity to 74,000 AF. For a comprehensive discussion of the history of the seepage problem and its effect on water supply yield of the Cedar/Tolt system, the reader is referred to Draper, et al. (1981).

SYSTEM DEMANDS AND CONSTRAINTS

Water Supply: The main purpose of the Cedar/Tolt system is to provide municipal and industrial (M & I) water to Seattle's approximately one million residents. Present M & I demand (1980) ranges from 12,000 AF/mo (200 cfs) during the winter, to 20,500 AF/mo (340 cfs) during the summer period; projected year 2000 demand ranges from 17,500 AF/mo (290 cfs) to 30,000 AF/mo (494 cfs).

Fish Requirements: A secondary purpose, which has taken on increased importance in recent years, is maintaining adequate flows for fish habitat. An ideal spawning habitat requires moderate summer flows, increasing gradually starting in early fall, and reaching a steady maximum rate that is maintained throughout the winter (Miller, 1976). Defining the precise flow values best for spawning, however, has been a source of controversy between the Department of Fisheries and the Seattle Water Department. Because these fish requirements limit the amount of water that can be withdrawn for water supply, they can be in direct conflict with supplying M & I demand during a severe drought.

Lake Washington Inflow: Lake Washington, a large freshwater lake within the Seattle metropolitan area, receives 70% of its average annual inflow from the Cedar River. Lake Washington is connected to Puget Sound, a large saltwater inlet, via a canal and locks system. Adequate lake inflows are necessary to maintain the elevation of the lake within acceptable bounds to prevent damage to shoreline structures and two floating bridges. Sufficient Cedar inflows also are required to insure adequate Lake Washington outflow through the locks, which is necessary for proper lockage operation, prevention of saltwater intrusion into Lake Washington, and salmon utilization of a fish ladder at the locks. Minimizing fluctuation of Lake Washington surface elevation is also desirable for recreational and aesthetic reasons.

Power Generation: Stored Cedar River water can generate up to 30 Megawatts (MW) of electricity. The average production rate is currently 11 MW. The production of hydropower is not considered a primary objective in the operation of the system, although proposed modifications to the generating system many change this.

CURRENT OPERATING POLICIES

Current policies for operation of the water supply system dictate that minimum fish flows be accorded higher priority than M & I supplies; withdrawals cannot be so large as to violate instream requirements downstream. This priority for fisheries is based on the Minimum Streamflow Act (Chapter 90.22 RCW), which allows instream requirements to be established "wherever it appears in the public interest".

Instream requirements have been established for the three sites shown in Figure 2. The requirements for the Main Stem Tolt, however, are not in effect in the current operating policy. Each minimum flow requirement is actually a pair of two values; one for normal conditions and one for drought conditions. During dry years, the State Department of Fisheries and the Seattle Water Department negotiate which set should be in effect at any given time (Draper, et al., 1981). On the Tolt River, water stored in the South Fork Tolt reservoir must be released to supplement natural inflow if it is necessary to meet the instream requirements. On the Cedar, however, stored water is not required to be released, even if streamflows fall below the required level. This policy difference is the result of different water laws being in effect at the time of reservoir construction.

The operating policy for Lake Washington is not clearly defined. A rule curve has been established by the Corps of Engineers that specifies the desired lake level elevation for each month of the year. The interpretation of the operating policy for the purpose of this study is given in Chapter 3.

The fraction of M & I water supplied by the Cedar River is usually 70% of the M & I demand. This leaves 30% of demand to be satisfied by the Tolt River. The Cedar River water is generally of higher quality than the Tolt River water (lower turbidity) and so is more desirable for water supply.

PROPOSED SYSTEM MODIFICATIONS

Seattle Water Department has investigated several potential modifications of the water supply system to increase system yield. The two major changes that currently appear most likely are:

1) Construction of a diversion dam on North Fork Tolt to divert water for M & I supply at a maximum rate of 18,000 AF/mo. If this option is pursued, minimum flow requirements for North Fork Tolt must be observed.

2) Increasing the height of the Cedar crib dam by 5 feet and using present dead storage in Chester Morse Lake. This is called the "City Light Plan" and would increase the Cedar reservoir active storage capacity by 36,100 AF, from 38,400 AF to 74,500 AF.

Chapter 3

DESCRIPTION OF THE MODEL

This chapter describes the interactive simulation model developed for the Cedar/Tolt Water Supply System. The chapter first describes the structure of the model in general terms, and then describes the two principal model sections in detail.

PURPOSE OF THE MODEL

The primary purpose of the Cedar/Tolt simulation model is to assist in real-time reservoir management during drought conditions. When the system is faced with possible shortages, the model is designed to display (in a probabilistic format) the effects of alternative management policies. The time frame for studying any particular drought is usually one to four months, depending on the length of the drought. Several droughts from the historical record can, however, be investigated in a single modeling session. Use of the model in this drought management mode is termed interactive use of the model.

The second purpose of the model is to provide a flexible and convenient tool for analyzing the yield of the system. When used for this purpose, the model evaluates the change in water yield resulting from various modifications to the system. The time frame for this use of the model is the entire historical record for weekly runoff data (1948-1980). This is termed non-interactive use of the model.

GENERAL CHARACTERISTICS OF THE MODEL

The model simulates operation of the Cedar/Tolt Water Supply System on a weekly time interval. Simulation results are expressed in terms of shortfalls in M & I supply, instream requirements, and Lake Washington target elevations, and as storage volumes of the two reservoirs. Hydropower generation is not included in the system simulation.

When used non-interactively, the model simulates the system for the entire time period desired and then provides summary statistics of deficits incurred. When used for drought management purposes (interactively), the model pauses if a shortage is predicted to occur during the next 12 weeks and displays current conditions, predicted flows and predicted shortages on a CRT display terminal. At this point, the user may evaluate and compare several management strategies, or may simply continue the simulation with previously defined operation policies.

CONCEPTUALIZATION OF THE SYSTEM

To represent the Cedar/Tolt system in mathematical terms, the system is divided into a series of nine reaches, as shown in Figure 4. Each reach contains one or more of the following elements:

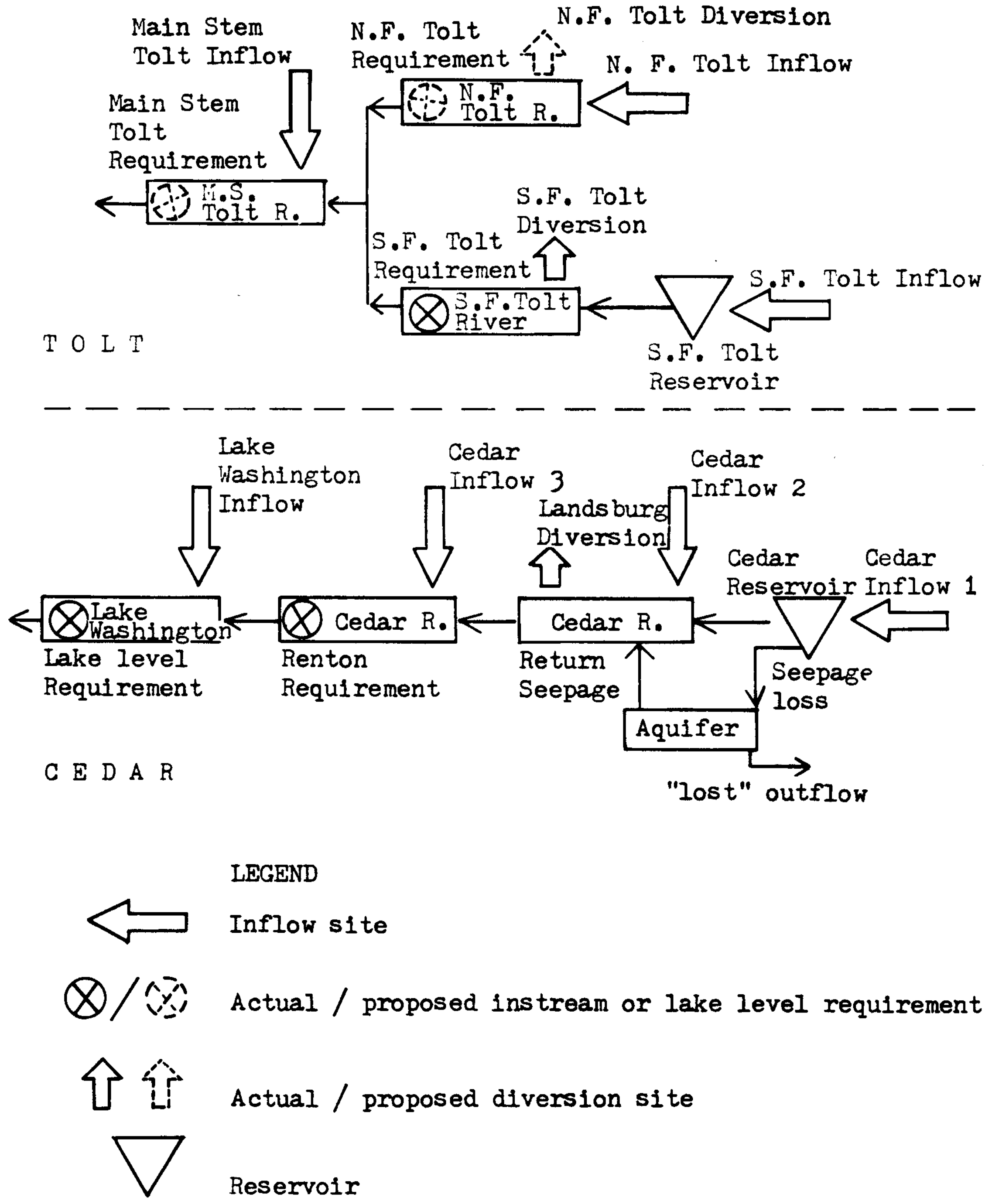
1) A reservoir
2) An in-stream flow requirement
3) A lake-level requirement
4) An inflow site
5) An outflow site
6) A diversion site for M & I supply

During each time step the model computes a water balance for each reach based on the continuity equation. For Lake Washington and the two reservoirs:

storage = previous storage + local inflow - releases - seepage - diversions

Figure 4.

Cedar/Tolt Water Supply System:
Model Conceptualization



For the river reaches:

Q downstream = Q upstream + local inflow - diversions

The local inflow term includes return seepage in the case of Cedar Inflow 2.

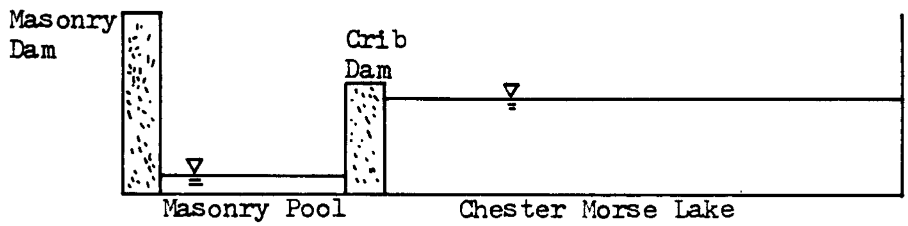
Determining seepage loss from the Cedar reservoir and return seepage to the river requires additional calculations. As mentioned in Chapter 2, the Cedar reservoir is actually a pair of two reservoirs in series (Figure 5). The lower reservoir leaks water at a substantial rate, and is kept near empty when possible. This policy allows the seepage rate to be calculated as a function of the total reservoir storage (masonry pool and Chester Morse Lake), and eliminates the need to model the Cedar reservoir as two separate units. The method of estimating seepage is based on the three possible storage configurations shown in Figure 5. When the total stored volume is less than Chester Morse Lake capacity (Figure 5a), seepage is estimated to be a constant minimum value of 650 AF/week, corresponding to 30 feet of water in the masonry pool. For volumes exceeding the Chester Morse Lake capacity (Figures 5b and 5c), seepage is a function of the volume in the masonry pool (Figure 6). The masonry pool volume computation differs, depending on whether or not the height in the masonry pool exceeds the crib dam height. If not (Figure 5b), masonry pool volume is equal to the total storage volume less the Chester Morse Lake volume. If the masonry pool elevation exceeds the crib dam height (Figure 5c), the masonry pool volume above the crib dam is assumed to be a set fraction (0.09) of the total storage above the crib dam.

All seepage loss from the reservoir is assumed to enter the aquifer adjacent to the reservoir. Return seepage to the Cedar River below the dam is assumed to be a non-linear function of aquifer storage (Figure 6), lagged by four

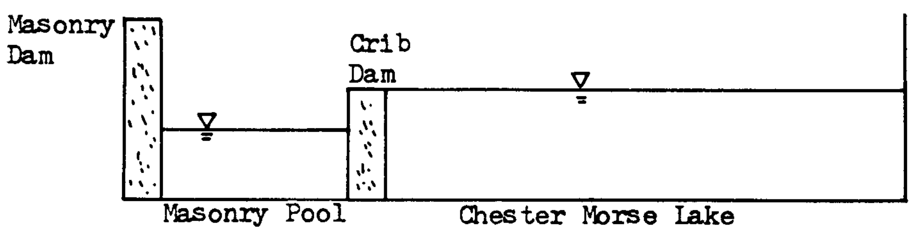
Figure 5.

Determination of Seepage Rates

a) Active Storage   30,000 AF
   Masonry Pool Volume = 1855 AF
   Seepage = 650 AF/week



b) 23,300 AF ∧ ≤ Active Storage   19,400 AF
   Masonry Pool volume = total active storage - 19,400
   seepage = function (Masonry pool vol.)



c) Active Storage ≥ 23,300 AF
   Masonry Pool volume = 0.09 * (Storage - 23,300 + 3900)
   Seepage = function (Masonry Pool volume)

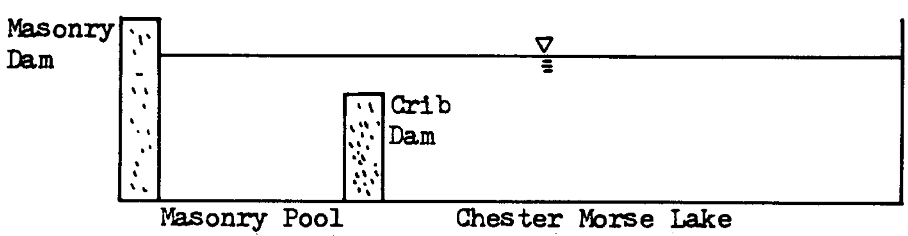
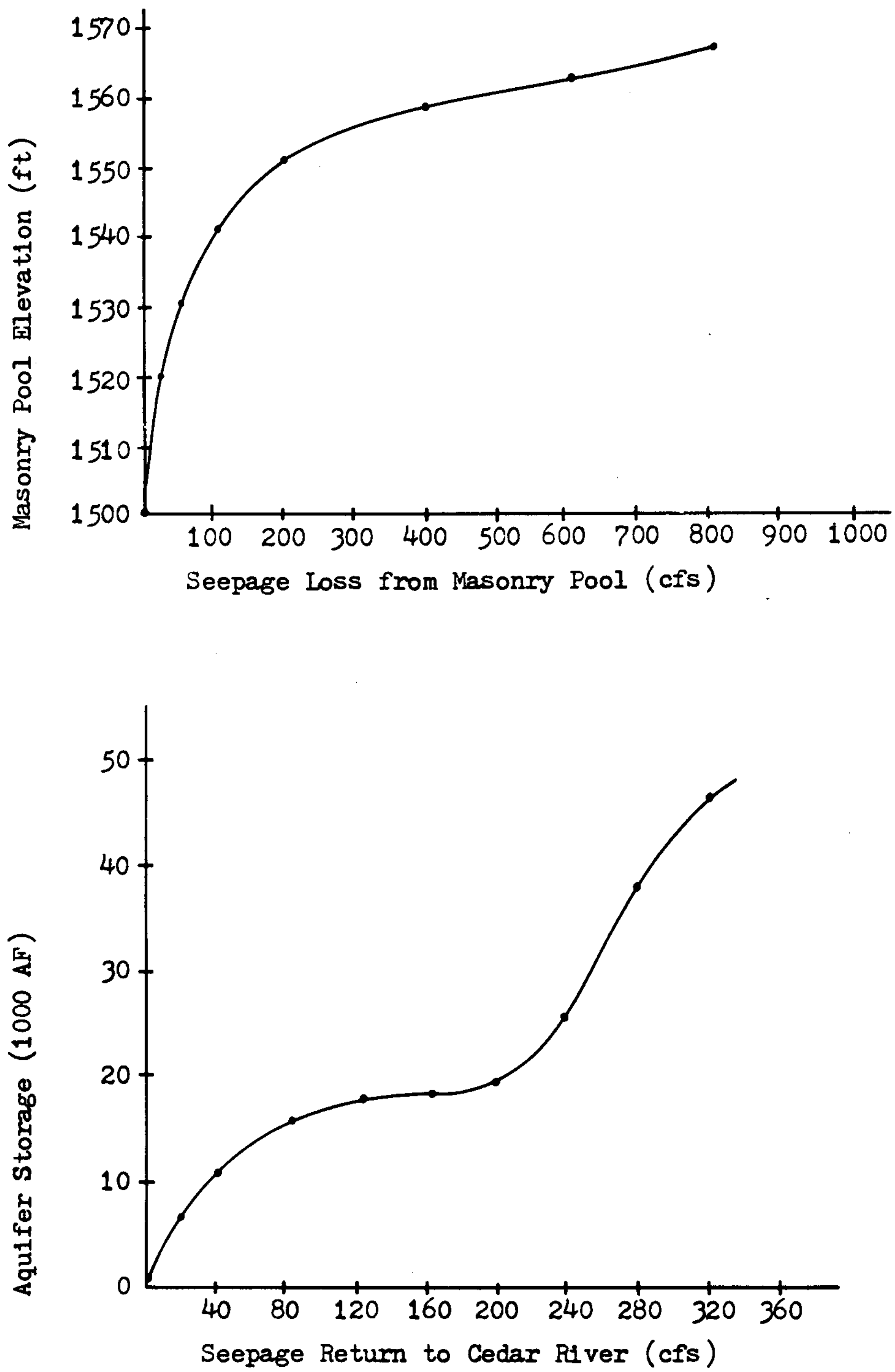


Figure 6.
Seepage Loss and Return Rates



weeks as estimated by the Corps of Engineers (COE), (COE, 1979). Roughly 80% of the masonry pool out-seepage can be expected to return to the river below the dam (Chen, 1976).

Lake Washington is modeled relative to its nominal 20-foot depth. It is assumed to have vertical banks for the range of depths modeled and a surface area of 22,100 acres. Inflow to the lake consists of the Cedar River flows and local inflow. Outflow from the lake consists of flow through the locks and fish ladder (the historical weekly average) and the saltwater drain which is assumed to be a function of lake volume.

OPERATING POLICIES

The general operating policy of the model is to satisfy minimum flow and lake level requirements before supplying M & I demand. This policy gives the minimum flow requirements first priority during a drought, and M & I supplies second priority.

The minimum flow requirement (normal or critical) to be in effect for the current week is defined according to the decision rules shown in Figure 7. The rules are based on the previous week's streamflow, the previous week's minimum flow requirement, and the current week's predicted inflow. When water supply is plentiful, the normal requirement is in effect. When water supply is low (as defined by the decision rules) either the critical requirement or natural inflow is specified, depending on the site. Water stored in the Cedar reservoir is not required to be used to meet instream requirements. Therefore, the required flow on the Cedar River during very dry weeks is natural inflow. For the South Fork Tolt River, stored water is required to supplement natural flow when necessary. Therefore, the critical set is always used during dry periods on the South Fork Tolt.

Figure 7.

Decision Rules for Instream Requirements

Requirement of Previous Week:	Flow of Previous Week (Q_{t-1})	Flow of Current Week (Q_t): $Q_t \geq$ Normal	$Q_t <$ Normal, $Q_t \geq$ Critical	$Q_t <$ Critical
Normal	$Q_{t-1} \geq$ Normal	Normal	Normal[1]	Critical[1]
	$Q_{t-1} <$ Normal, $Q_{t-1} \geq$ Critical	Normal	Critical	Critical[1]
	$Q_{t-1} <$ Critical	Normal	Critical	Critical[1]
Critical	$Q_{t-1} \geq$ Normal	Normal	Critical	Critical[1]
	$Q_{t-1} <$ Normal, $Q_{t-1} \geq$ Critical	Critical	Critical	Critical[1]
	$Q_{t-1} <$ Critical	Critical	Critical	Natural Flow[2]
Natural	$Q_{t-1} \geq$ Normal	Critical	Critical	Natural[2]
	$Q_{t-1} <$ Normal, $Q_{t-1} \geq$ Critical	Critical	Critical	Natural[2]
	$Q_{t-1} <$ Critical	Critical	Natural[2]	Natural[2]

1 Requirement = Natural for the N. Fork Tolt

2 Requirement = Critical for the S. Fork Tolt

The policy for satisfying Lake Washington requirements is as follows:

1) If the elevation falls below the required elevation for the current week, the minimum of the following three quantities is released:

1) volume necessary to reach required elevation

2) natural inflow

3) natural outflow through locks

2) If the elevation falls below 20 feet, sufficient stored water is released to restore the lake level to 20 feet.

Allocation of M & I demand between the two rivers is accomplished by applying a modification of the space rule, first defined by Maass et al. (1962). The purpose of the space rule is to minimize the amount of water that is needlessly spilled from the reservoirs. This is accomplished by equalizing the end-of-week ratio of freeboard to capacity of the two reservoirs. The basic equations are:

$$\frac{\text{Freeboard 1}}{\text{Capacity 1}} = \frac{\text{Freeboard 2}}{\text{Capacity 2}}$$

where Freeboard = Capacity - storage (t-1) + inflow (t) - release (t)

and release 1 (t) + release 2 (t) = M & I demand

The inflows included in the equation represent forecasts of the current week and following 3 weeks. Because the actual inflows may differ substantially from those forecasted, the space rule does not always result in the reservoirs being drawn down evenly. The following week's allocation, however, usually compensates for earlier poor forecasts. Because the releases are updated weekly, the negative impacts of poor forecasts are minimized.

MODEL REQUIREMENTS

The model requires weekly historical inflows at the seven sites shown in Figure 4. Data compilation procedures are described in Appendix A. Data were available for water years 1948 through 1980.

Probabilistic streamflow forecasts ranging from one to 16 weeks are also required for each site. The streamflow predictor, described in Chapter 4, provides variable length forecasts for low, average, and high flow conditions, corresponding to roughly 10, 50, and 90 percentile probability levels. (Streamflows less than or equal to the low estimate can be expected about 10% of the time.) The following values are also required for each week of the year:

1) Active storage capacities (Figure 8), where
   active storage = total storage -flood storage -dead storage
2) Instream flow requirements (Figure 10)
3) Lake level requirements (Figure 11)
4) M & I demand (Figure 9)
5) Lake Washington outflow through the locks and fish ladder (Figure 11)

STRUCTURE OF THE MODEL

The model consists of two major sections: the first controls the interactive functions (communication with the user), and the second controls the physical simulation of the system. The model is further divided into several subprograms, as shown in Figure 12, for purposes of organization, efficiency, and ease of modification.

The interactive section of the model controls the following subprograms:

1) READ - reads in all input data required.

2) GRAPH - provides a graphical display of past and predicted storage volumes and M & I deficits for both reservoirs.

Figure 8.

Reservoir Active Storage

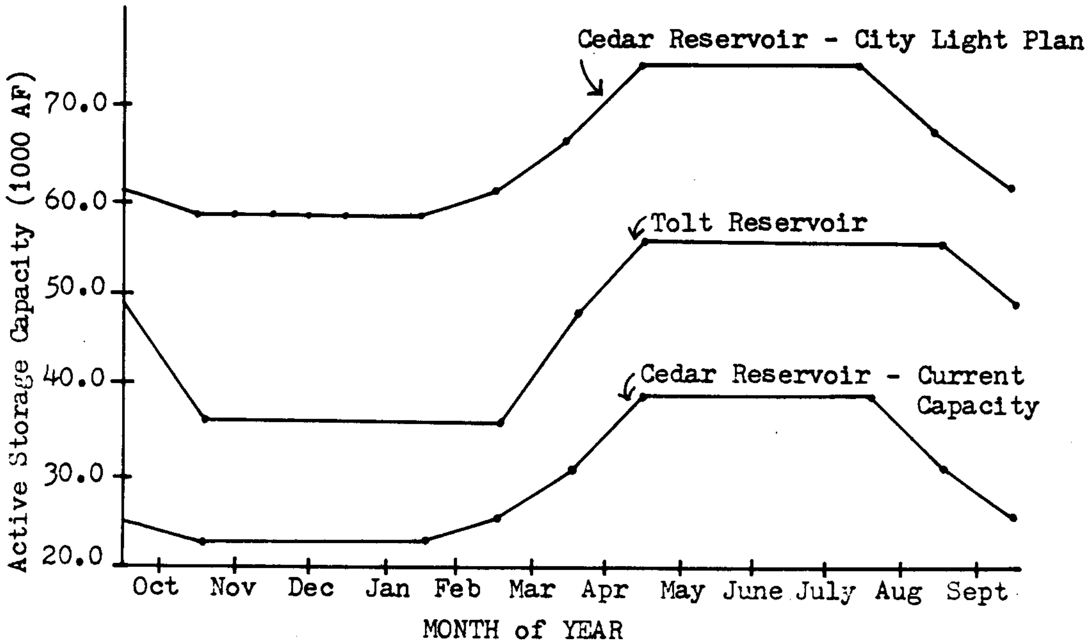


Figure 9.

Municipal and Industrial Demand Pattern

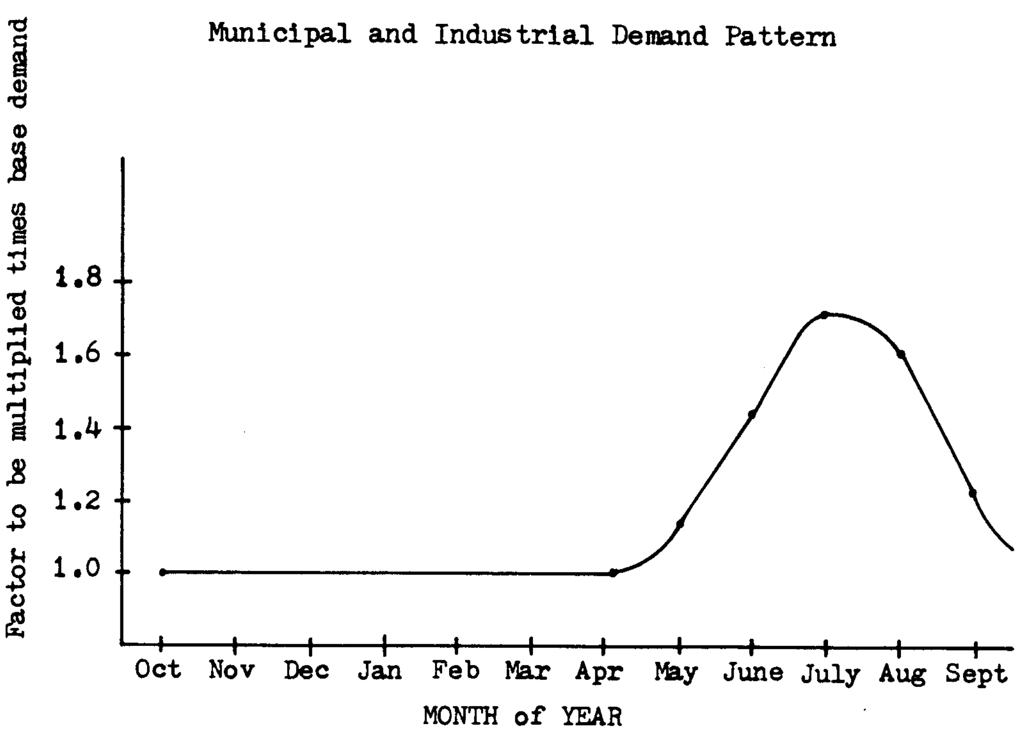


Figure 10.
Instream Requirements

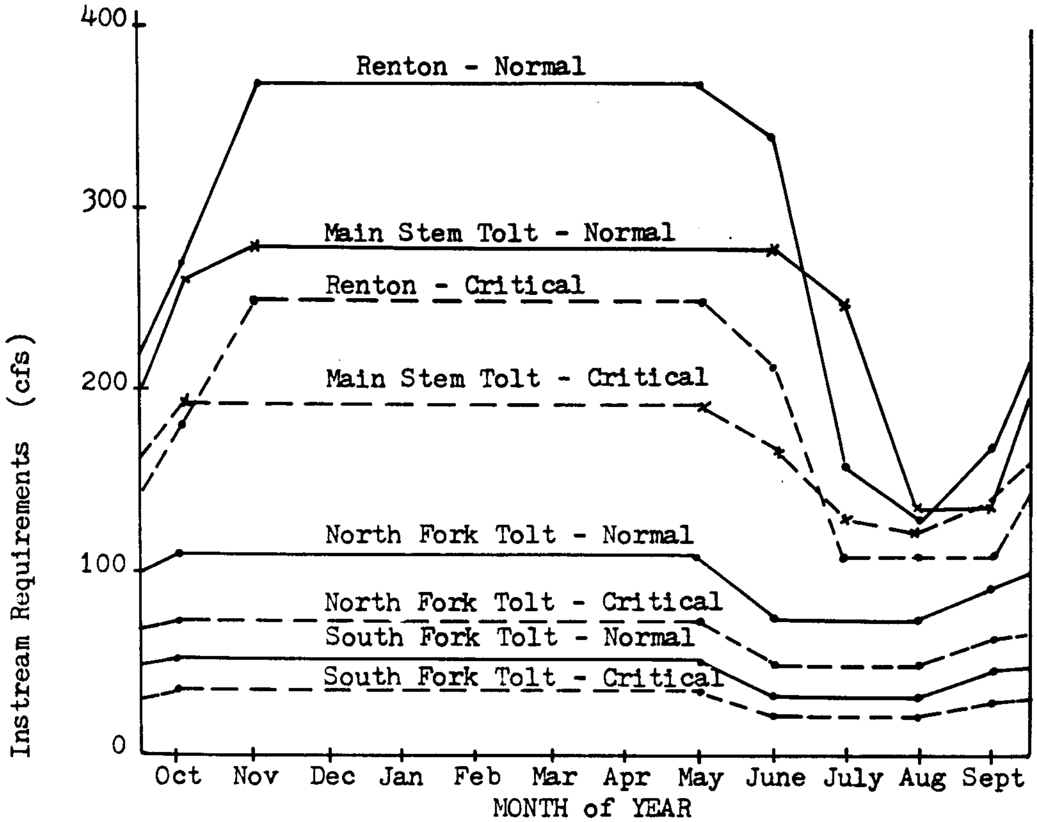


Figure 11.
Lake Washington Historical Average
Outflow and Rule Curve

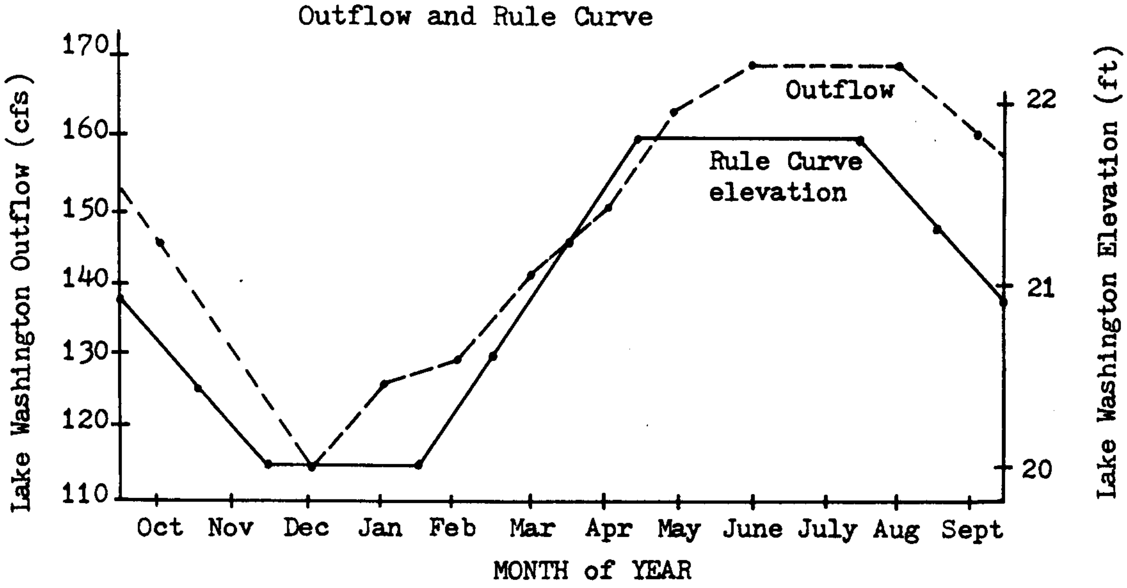
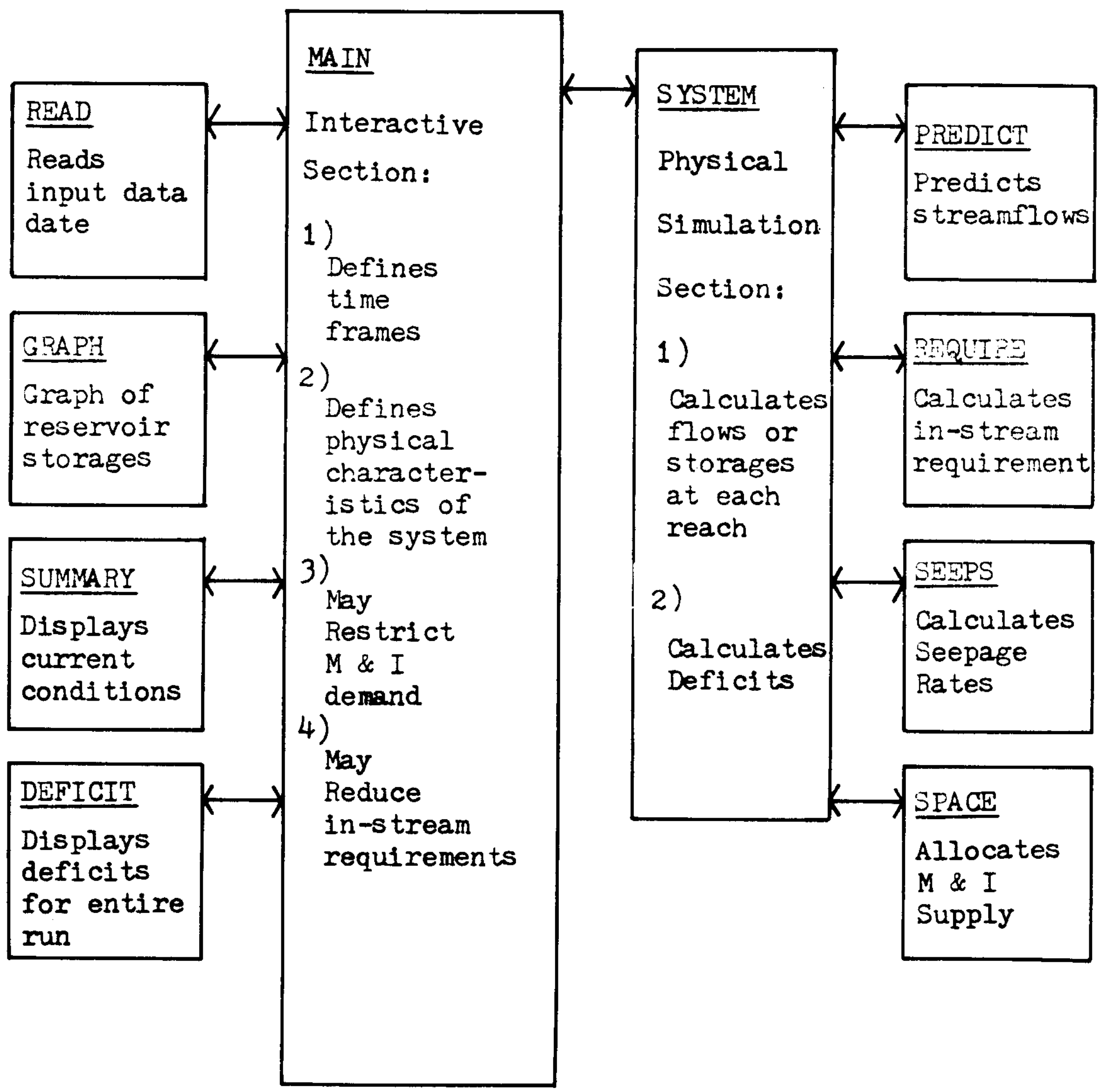


Figure 12.

Structure of the Cedar/Tolt Simulation Model



3) SUMMARY - provides a summary of predicted storages, flows, deficits, and lake levels for the current week.

4) DEFICIT - provides a summary of all deficits (M & I, instream flows, and lake levels) incurred during the length of the run. This is displayed at the end of the modeling session.

The simulation section of the model controls the following subprograms:

1) PREDICT - provides low, average, and high streamflow forecasts for 1, 4, 12, or 16 weeks, as described in Chapter 4.

2) REQUIRE - determines which instream flow requirement is to be in effect for the current week: normal or critical.

3) SEEPS - calculates seepage loss from the Cedar reservoir and seepage return downstream of the dam.

4) SPACE - allocates the M & I supply between the Tolt and Cedar river reservoirs according to the space rule.

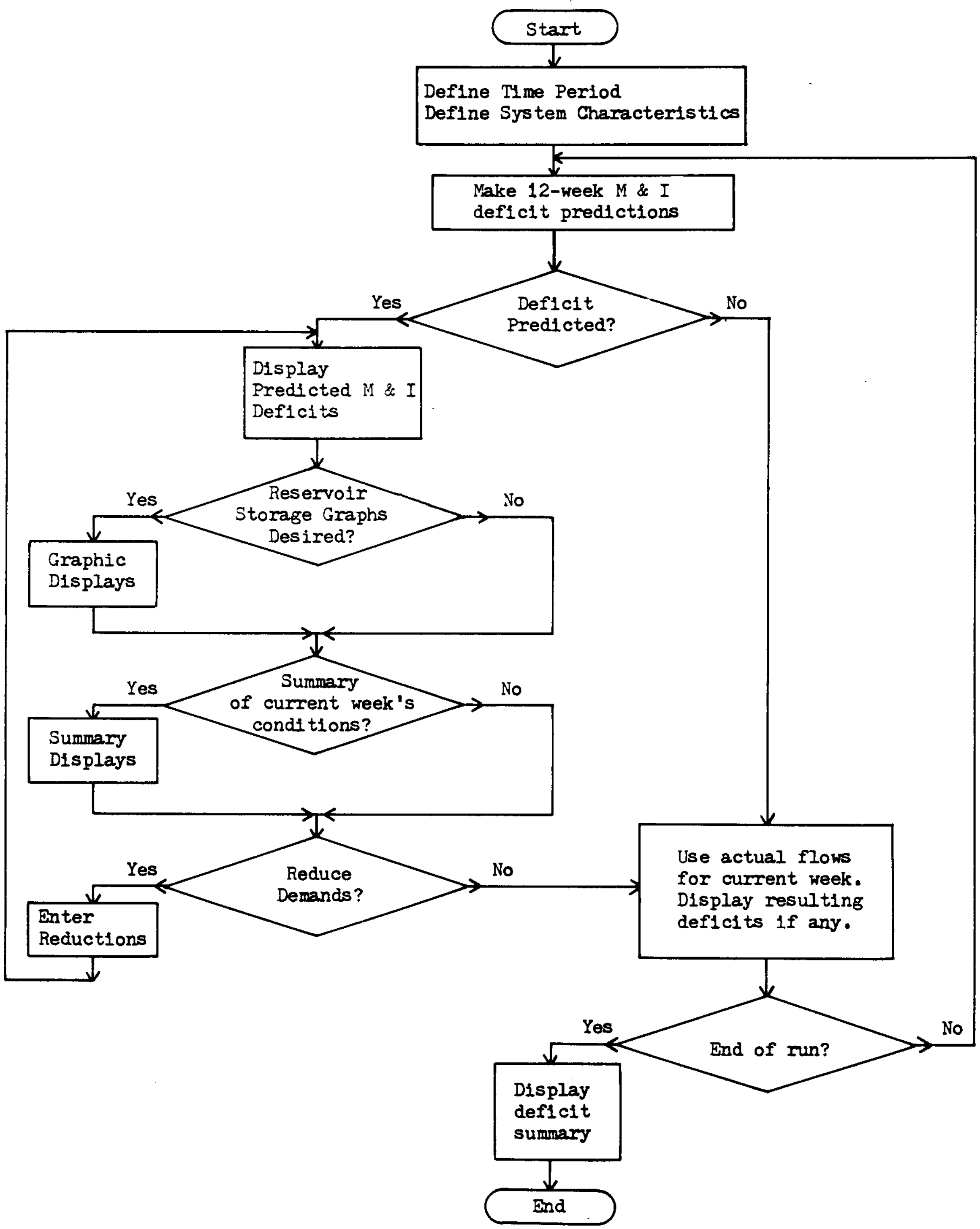
INTERACTIVE SECTION

The interactive section is best described with a step-by-step account of how the model works. A simplified flow chart of this section is shown in Figure 13.

Initiating the Session: The user begins a modeling session by entering the initial year (1948 through 1980) and final year of the run. The model then calls the subprogram READ, to read all of the necessary data for the appropriate years.

The user is then asked to define certain system characteristics that will be in effect for the entire length of the run. These include physical characteristics, general operating policies, and the base level of M & I demand. The user indicates which of the following options are to be in effect:

Figure 13.
Flow Chart of the Interactive Section



1) a) Active Cedar storage capacity #1 (current capacity).

b) Active Cedar storage capacity #2 (City Light Plan). Storage in the Cedar reservoir is increased by 36,100 AF in Plan #2, by using what is currently dead storage.

2) a) North Fork Tolt dam in existence

b) No North Fork Tolt dam

3) a) Lake Washington lake level maintained above 20 feet in elevation using stored water

b) Stored water not used to maintain lake level

4) a) Lake Washington rule curve in effect requiring natural inflow

b) Rule curve not in effect

5) a) Minimum flow requirements in effect for the Main Stem Tolt

b) Main Stem Tolt requirements not in effect

The user then enters numerical values for the following:

1) M & I base level of demand. (Weekly demand varies as shown in Figure 9.) Default value is 6000 AF/week (430 cfs).

2) Space Rule factor. This factor specifies what additional percentage of M & I demand is to be taken out of the Cedar River, in addition to what is determined by the space rule. See Draper, et al. (1981), p 98, for an explanation of the implications of this modification.

Yield Study: If the model is being run in non-interactive mode, no further user participation is required. The historical flows for the period indicated are used, and a summary of deficits is provided at the end of the run.

Drought Management: If the model is being used for drought management (interactive mode), there is a pause whenever an M & I deficit is predicted within the next 12 weeks, and user input is requested. This 12 week screening process provides an appropriate lead time for dealing with future uncertainties. An M & I deficit occurs only when both reservoirs are completely empty (after satisfying the minimum requirements for the week) and represents a very dire situation. Therefore, even if a forecasted shortage is 12 weeks away, measures may need to be implemented immediately to lessen the severity of the drought.

The model starts the session at the beginning of the second week of the period indicated. The streamflow forecasting subprogram PREDICT is called, and low, average, and high forecasts are made for each site. The low estimate (approximate 10 percentile flow) is always used for the 12-week screening procedure.

If a deficit is not forecasted based on the low flow estimate, it is assumed that no operating changes are to be made, and the actual inflows for the current week are processed. If a deficit occurs during this week (although not forecasted) the user is shown the magnitude and location of the deficit. It is not possible, however, to make any retroactive changes, even if an unpredicted deficit occurs (this would be expected to happen only rarely). Deficit or not, the model moves ahead to the next week and repeats the 12 week forecast. During high flow periods, the model may proceed through several months without user participation.

The model continues in this manner until a deficit is forecasted during the next 12 weeks with the low streamflow estimate. When this occurs, the model displays a table of predicted M & I deficits resulting from the low, average, and high inflows for each of the following 12 weeks, as shown in Figure 14. The user then has 3 opportunities to interact with the model: 1) request a graphical display of predicted storage volumes, 2) request a summary of conditions predicted for the current week, and 3) specify changes in operating policies.

Figure 14. Predicted Deficits

CURRENT WEEK = AUG 13, 1958 (WEEK NUMBER 98 OUT OF 208)

THE FOLLOWING M & I SHORTAGES ARE PREDICTED
TO OCCUR IN THE NEXT 12 WEEKS, FOR THE LOW, AVERAGE AND
HIGH FLOW FORECASTS: (1000 AF)

WEEK	LOW	AVE	HIGH
1	0.00	0.00	0.00
2	0.00	0.00	0.00
3	0.00	0.00	0.00
4	0.00	0.00	0.00
5	3.01	0.00	0.00
6	5.88	0.00	0.00
7	6.46	0.00	0.00
8	6.50	3.09	0.00
9	5.29	0.00	0.00
10	6.48	1.68	0.00
11	4.74	0.00	0.00
12	3.88	0.00	0.00

Figure 15. Graph of Predicted Storage Reservoirs

```
STORAGE (*) IN % OF CAPACITY AND M & I DEFICITS (-) IN % OF DEMAND
     FORECAST PERIOD= 12 WEEK(S)         FLOW SEQUENCE= AVERAGE
               CEDAR                              TOLT
100+ *                            |  *                          +100
   |*                             |** *                         |
   |  *                           |    *                        |
 80+   **                         |     *                       + 80
   |     **                       |      **                     |
   |       *                      |        *                    |
 60+        *                     |                             + 60
   |         *                    |         *                   |
   |          *         -         |          *         -        |
 40+                              |           *                 + 40
   |           *                  |            *                |
   |            *                 |             *               |
 20+             *        -       |              *       -      + 20
   |              **              |               *             |
   |                *             |                **      *    |
 00+----+----+----+--********-----+----+----+----+---******+----+ 00
  32   37   42   47   52   57    32   37   42   47   52   57
                  ^                              ^
               WEEK      (CURRENT WEEK=  46 (^), AUG 13, 1958)
TO STORE GRAPH, ENTER AN I.D. NO. FROM 1 TO 5; OTHERWISE, ENTER A ZERO:
       2
```

1) Graphical Display: If requested, a plot of predicted storage volumes for the Cedar and Tolt reservoirs is displayed on the screen as in Figure 15. The Cedar reservoir is shown on the left side; the Tolt on the right. The user specifies which inflow sequence (low, average, or high) and forecast length (1, 4, 12, or 16 weeks) are to be used. Storage volumes are shown for the preceding 13 weeks, and for each week of the forecast period.

When the reservoirs are completely empty, it is important to know the extent of the resulting deficits. Therefore, M & I deficits are plotted when they occur with a contrasting symbol, as shown in Figure 15. Storage volumes are expressed in terms of percent of reservoir capacity, and M & I deficits are expressed in terms of percent of demand. Deficits are plotted on both the Cedar and Tolt portions of the plot.

At this time, the user may wish to save the current graph for later comparisons with graphs resulting from different inflow sequences, forecast lengths, or operating policies. To do this, the user indicates the memory location (any integer from one to five) into which the graph is to be stored. The graph is then available for future reference, as long as the storage location is not later used for another graph (a maximum of five can be stored). If additional storage graphs are desired for different forecast lengths or probability levels (low, average, or high inflow sequences), these can be requested at this time. The user is prompted for the appropriate information.

To compare two graphs, the user specifies the appropriate two memory locations, and the model "overlays" the two graphs as shown in Figure 16. The symbols of the first graph are changed to a contrasting symbol. Where two points overlap, only the second symbol is shown. The memory location, associated symbols, inflow sequence, and forecast length are identified for each graph. The graphical displays are currently programmed within the confines of a low cost, 26 by 80 CRT grid to insure transportability. However, finer grids are becoming available at much lower cost; considerable improvement in the quality of the graphical displays could be achieved by utilizing more sophisticated graphics software.

2) Summary of Current Week Predictions: A summary of predictions for the current week can be requested. This display, shown in Figure 17, provides the low, average, and high estimates for streamflows, lake levels, and M & I supplies, along with the current requirements. It indicates with an asterisk (*) which requirements are binding and, therefore, may be likely candidates for relaxation. The summary also provides low, average, and high estimates for the end-of-week reservoir storage volumes and their capacities.

3) Changes in Operating Policies: The user now has the opportunity to make the following system modifications for the current week:

a) Reduce minimum streamflow requirements: a percentage reduction is entered for each site.

b) Reduce Lake Washington "rule curve" requirements: percentage reduction is entered.

c) Reduce Lake Washington minimum elevation for which stored water is required.

d) Institute restrictions on M & I supply: percentage reduction is entered.

If any of these changes are made, the system is rerun for the next 12 weeks with the same set of low, average, and high inflow forecasts previously generated. The user then has the opportunity to compare predicted storage volumes resulting from different operating policies.

Figure 16. Comparison of Two Operating Policies

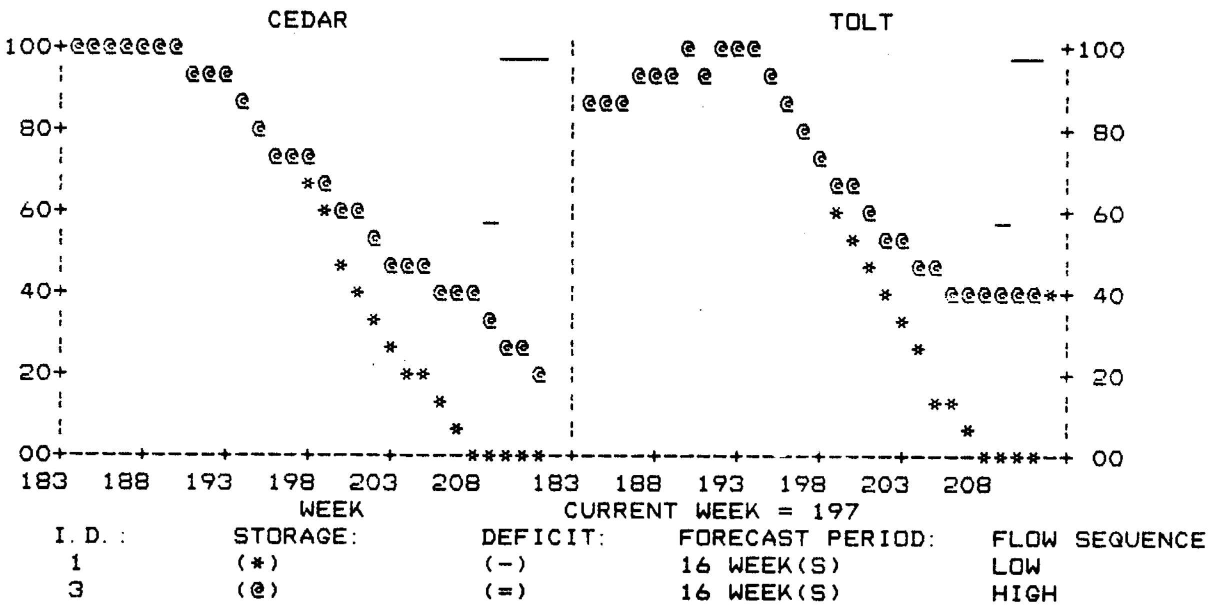


Figure 17. Summary of Current Conditions

CURRENT WEEK = AUG 13, 1958 (WEEK NUMBER 98 OUT OF 208)
SUMMARY OF PREDICTED END-OF-WEEK CONDITIONS (* MEANS REQ. IS BINDING)

RESERVOIR STORAGES	LOW	AVERAGE	HIGH	CAPACITY
CEDAR (1000 AF)	16.3	16.9	17.8	71.0
TOLT (1000 AF)	14.0	14.5	15.2	56.0
RIVER SITES (1000 AF/WK)	**LOW**	**AVERAGE**	**HIGH**	**REQUIRED**
RENTON	1.8 *	1.8	1.8	1.8
NORTH FORK TOLT	0.5 *	0.6 *	0.6 *	0.6
SOUTH FORK TOLT	0.5	0.3 *	0.3 *	0.3
MAIN STEM TOLT	1.0 *	1.1	1.3	1.0
RULE CURVE (FT)	21.6	21.6	21.6	21.6
20 FT ELEV. (FT)	21.6	21.6	21.6	0.0
M & I SUPPLY (1000 AF/WK)	10.7	10.7	10.7	10.7

At this time, the user decides which operating policy gives the most desirable results. This decision is based on the risk level acceptable to the user for water shortages and the relative importance of instream requirements in relation to M & I supply. After the final operating policies are specified, the actual inflows for the current week are processed, and the resulting end-of-week conditions displayed, as shown in Figure 18.

The model then moves ahead to the next week and again makes a 12 week prediction of inflows and deficits, assuming the original values for instream requirements and M & I demand. Simulation of the system is interrupted only when a deficit is predicted with the low inflow forecasts. The model continues in this manner for the length of the run.

After all indicated weeks have been processed, the subprogram DEFICIT is called, which calculates summary statistics for the length of the run (Figure 19). DEFICIT provides the average, maximum and total deficit, and the number of weeks a deficit occurred for:

1) Renton requirements,
2) North Fork Tolt requirements,
3) South Fork Tolt requirements,
4) Main Stem Tolt requirements,
5) Lake Washington rule curve,
6) Lake Washington 20-foot requirement,
7) M & I demand,
8) Total deficit relative to the Lake Washington rule curve, and
9) Total deficit relative to the Lake Washington 20-foot elevation.

Figure 18. End-of-Week Conditions

CURRENT WEEK = OCT 1, 1951 (WEEK NUMBER 209 OUT OF 520)
RESULTS OF USING ACTUAL FLOWS:

SITE	DEFICIT (1000 AF)		RESERVOIR	STORAGE	CAPACITY
RENTON	0.00	(0. CFS)	CEDAR	0.00	61.00
N.F. TOLT	0.00	(0. CFS)			
S.F. TOLT	0.00	(0. CFS)	TOLT	0.58	51.00
MAIN TOLT	0.40	(29. CFS)			
LAKE WASH.	0.00	(0.0 FT)			
M & I	0.00	(0. CFS)			

Figure 19. Deficit Summary

DEFICIT SUMMARY
LENGTH OF RUN = 208 WEEKS (1957 - 1960)
SYSTEM CHARACTERISTICS:

1)	"CITY LIGHT" PLAN IN EFFECT?	YES
2)	N. FORK TOLT DIVERSION DAM EXISTS?	YES
3)	LAKE WASHINGTON RULE CURVE IN EFFECT?	YES
4)	LAKE WASHINGTON 20 FT. ELEV. MAINTAINED?	NO
5)	MINIMUM FLOW REGIREMENTS- MAIN TOLT?	YES
6)	BASE M&I DEMAND LEVEL (1000 AF/WEEK)	6.50
7)	SPACE RULE FACTOR	0.00

SYSTEM DEMAND	AVERAGE DEFICIT (1000 AF)	MAXIMUM DEFICIT(1000 AF)	CUMULATIVE DEFICIT(1000AF)	NO. OF WEEKS
M & I SUPPLY	3.68 (264. CFS)	5.63 (404. CFS)	25.75	7
LW RULE CURVE	1.94 (0.1 FT)	3.50 (0.2 FT)	50.47	26
LW 20 FT ELEV	0.00 (0.0 FT)	0.00 (0.0 FT)	0.00	0
RENTON REQ.	0.86 (62. CFS)	1.20 (86. CFS)	1.72	2
N.F. TOLT REQ.	0.00 (0. CFS)	0.00 (0. CFS)	0.00	0
S.F. TOLT REQ.	0.00 (0. CFS)	0.00 (0. CFS)	0.00	0
MAIN TOLT REQ	0.30 (22. CFS)	0.93 (67. CFS)	14.27	47
TOTAL (LWRC)	1.44	6.72	92.21	64
TOTAL (LW20')	0.80	6.72	41.74	52

PHYSICAL SIMULATION OF THE SYSTEM

The physical simulation section calculates flow rates and storage volumes for each of the reaches shown in Figure 4. A flow chart of this section is shown in Figure 20.

The simulation section begins by defining the local inflows for the current week. These are either forecasted or actual flows, as specified by the interactive section. The model then calls the subprogram REQUIRE to determine which set of instream requirements is in effect: normal or critical, according to the decision rules described previously. If any reductions in requirements or M & I demand have been specified by the user, these are incorporated.

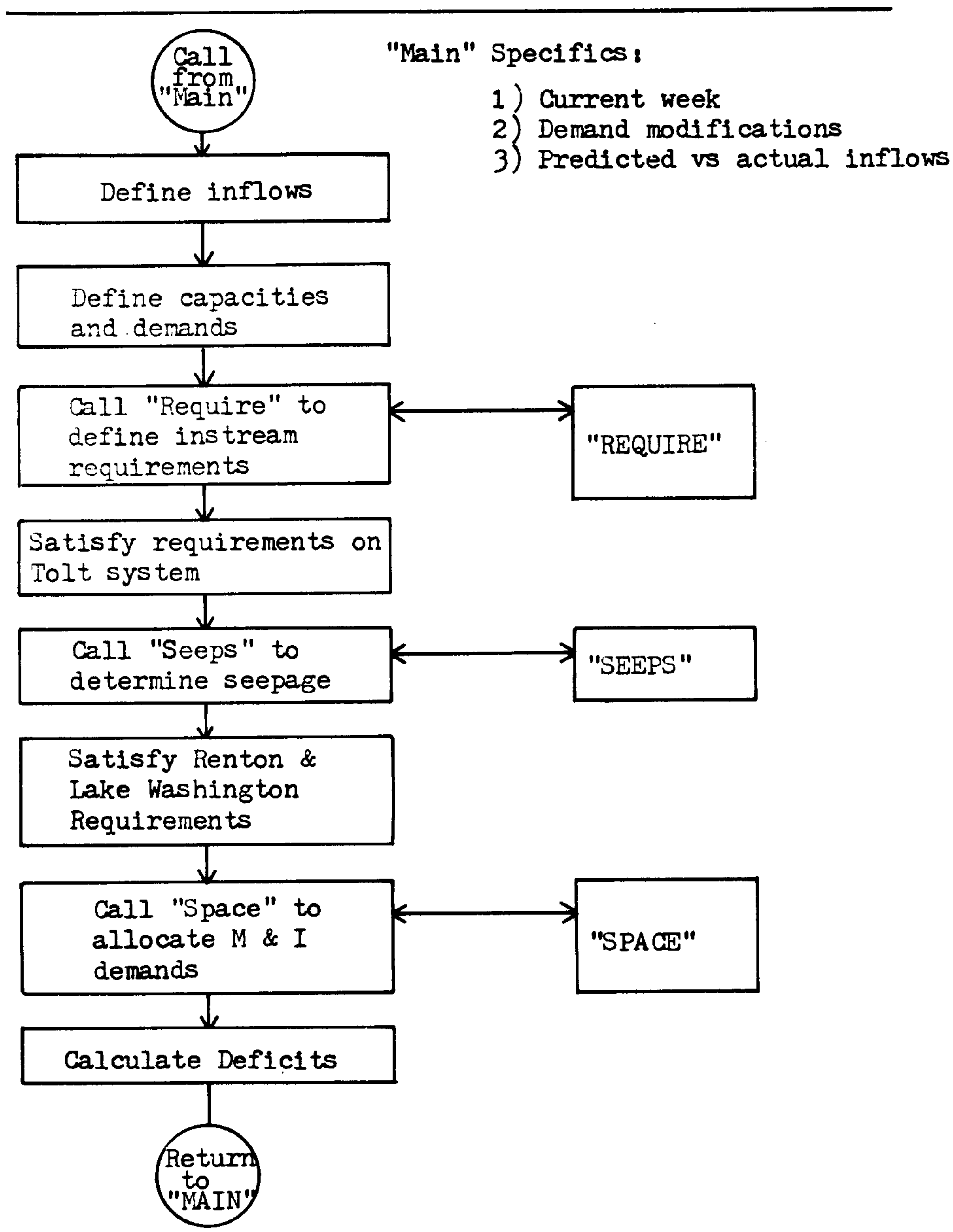
Simulation begins with the Tolt River. Initially, it is assumed that no releases are made from the South Fork Tolt reservoir. Flow rates for each reach are calculated using the continuity equation. If the instream requirements are not satisfied on the South Fork or Main Stem, the necessary volume from the South Fork reservoir is released.

The model then proceeds to the Cedar River. The subprogram SEEPS is called to calculate seepage loss from the Cedar reservoir and return seepage to the river as described previously. The flow rate at Renton and Lake Washington elevation are then calculated taking into account Cedar Inflows 2 and 3 and return seepage, but assuming no reservoir releases. Three separate requirements may necessitate a release from the Cedar reservoir:

1) Renton instream requirements; natural inflow only.
2) Lake Washington rule curve; natural inflow only.
3) Lake Washington 20-foot elevation; stored water required.

Figure 20.

Flow Chart of the Physical Simulation of the System



The draft required to satisfy each of these requirements is calculated, and the maximum of these three volumes is then released.

M & I Demand: If water in excess of that needed for instream flow requirements exists at Landsburg or in the North Fork Tolt (if the North Fork diversion option has been selected), this water is diverted for M & I supply. The remaining M & I demand must be satisfied from storage in the two reservoirs. The amount to be released from each reservoir is specified by the subprogram SPACE, utilizing the space rule described earlier.

Deficits: After the final reservoir releases are made, the end-of-week reservoir storage volumes Lake Washington elevation, and river flow rates are determined. Instream shortfalls and M & I deficits are calculated and stored for later display. At this point, the model either begins a new week of simulation or returns to the main section for further interaction with the user.

Examples and results of modeling sessions are provided in Chapter 5. These examples further illustrate the capabilities of the model. In addition, a partial listing of the computer model is provided in Appendix C.

Chapter 4

STREAMFLOW FORECASTING

FORECASTING NEEDS

Real-time reservoir management requires estimates of future inflows. Short-term forecasts (1-4 weeks) are needed to assist in decisions on the week's releases, and longer term forecasts are needed for planning purposes. The Cedar/Tolt simulation model described in Chapter 3 is designed to use streamflow forecasts of 1, 4, 12, and 16 weeks.

In addition to estimates of "most-likely" streamflows, information is needed on the probabilities of future events. The streamflow forecasting methods described in this chapter provide estimates of the approximately 10, 50, and 90 percentile flows for each of the seven inflow sites shown in Figure 4. These are referred to in the model as the low, average, and high estimates.

METHODOLOGY

Two approaches were investigated to provide streamflow forecasts. The first was a modification of a lag-one Markov model. The second was a more complex forecasting model based on the National Weather Service River Forecasting System (NWSRFS) used in extended streamflow prediction (ESP) mode. This second method, called the modified ESP method, was developed and applied to Cedar Inflow Site 1 (Figure 4) with the intent of evaluating the ESP forecasts to determine if the method should be applied to the other six sites. The lag-one Markov model is discussed first.

MARKOV MODEL

The Markov model as used for streamflow forecasting was first introduced by Thomas and Fiering (1962) and has since been widely used in a variety of water resource applications. A lag-one Markov model assumes that the forecasted flow is a function of only the flow in the previous time period. In forecast model, the most-likely, or 50 percentile flow, is equal to the mean plus a multiple of the previous period's deviation from the mean. The basic Markov equation for multiple seasons is, assuming a logarithmic flow transformation is:

$$Q_{i,j(50)} = \mu_j + \frac{\rho_{j,j-1}\,\sigma_j}{\sigma_{j-1}}\,(Q_{i,j-1} - \mu_{j-1})$$

where $Q_{i,j(50)}$ = the natural logarithm of the 50 percentile forecast period streamflow

$Q_{i,j-1}$ = the natural logarithm of the previous week's streamflow

$\rho_{j,j-1}$ = the correlation coefficient between the forecast period streamflow and the previous week's streamflow in log space

μ_j, μ_{j-1} = mean of forecast and previous week's flows in log space

σ_j, σ_{j-1} = standard deviation of the forecast and previous week's flows in log space

The choice of a log normal distribution was based on the observed positive skewness of the weekly flows, and the simplicity of this transform. To check the validity of this distribution, the sample skew coefficient of the natural logarithms of the flows for each week, each forecast period and each site was calculated. Assuming the actual skew is zero, and a sample size of 33 (the length of record), there is a 95 percent chance that the sample skew would be within +0.829 and -0.829 (Matalas and Benson, 1968). The sample skew coefficient was found to be within this range 89% of the time. Based on these results, a hypothesis that the flow logarithms have zero skew could not be disproved and log normal transformations were used in the work that follows. For the remaining 11% of the cases when the sample skew coefficient was outside of this range, a more appropriate distribution could have been found. For simplicity and consistency, however, the log normal distribution was used for all cases.

The number of previous weeks to include in the model was tested for all forecast periods. The correlation coefficient, $\rho_{j,j-1}$, between the forecast period streamflow volume (1, 4, 12, or 16 weeks) and the previous 1, 2, and 3 week streamflow volume was calculated. In each case, the highest correlation coefficient was obtained by using only the previous week's flows.

Estimating Parameters: To preserve the mean and standard deviation of the forecast flows in real space, the log normal transformation method described in Burges and Hoshi (1978) was used to determine μ , and σ. Streamflow, assumed to be a random variate X with mean μ_x, and variance σ_x^2, was transformed to a normally distributed random variate Y with mean μ_y and variance σ_y^2 via Y = ln X.

When x represents the forecast period flows, $\mu_j = \mu_y$ and $\sigma_j = \sigma_y$. When x represents the previous weeks flows, $\mu_{j-1} = \mu_y$ and $\sigma_{j-1} = \sigma_y$.

The appropriate equations are then:

$$\sigma_y = \left[\ln \left(\left(\frac{\sigma_x}{\mu_x}\right)^2 + 1\right)\right]^{1/2}$$

$$\mu_y = \ln \mu_x - \frac{1}{2}\sigma_y^2$$

The correlation coefficient $\rho_{j,j-1}$ was calculated in the following manner using the natural logarithms of the flows:

$$\rho_{j,j-1} = \frac{\frac{1}{n-1}\sum_{i=1}^{n-1} Q_{i,j}\,Q_{i,j-1} - \bar{Q}_{i,j}\,\bar{Q}_{i,j-1}}{\sqrt{\frac{1}{n-1}\sum_{i=1}^{n-1}(Q_{i,j}-\bar{Q}_{i,j})^2}\sqrt{\frac{1}{n-1}\sum_{i=1}^{n-1}(Q_{i,j-1}-\bar{Q}_{i,j-1})^2}}$$

where n = 33, the length of record

i = the year (1 to 33)

j = the week (1 to 52)

Because the sample size, 33, is quite small, the sample standard deviation and correlation coefficients for each week of the year reflect considerable sampling variability and do not represent the smooth seasonal variation expected of their population values. To reduce the sampling variability, the calculated values were replaced by a five-week moving average.

<u>Ten and 90 percentile flows</u>: The forecast variance is given by:

$$\sigma_j^2 = \sigma_j^2 \,(1 - \rho_{j,j-1}^2)$$

The ten percentile flow is represented by a value approximately 1.28 standard deviations below the mean (assuming a normal distribution), and the 90 percentile flow by a value approximately 1.28 standard deviations above the mean. Therefore:

$$Q_{(10)} = Q_{(50)} - 1.28\,\sigma_j\sqrt{1 - \rho_{j,j-1}^2}$$

$$Q_{(90)} = Q_{(50)} + 1.28\,\sigma_j\sqrt{1 - \rho_{j,j-1}^2}$$

These equations give the forecast period sums for any forecast period at any site.

To disaggregate the forecast sums to weekly flows, the historical pattern of flows for the appropriate weeks is used:

$$Q_k = Q_{sum} * \left(\frac{\bar{Q}_k}{\bar{Q}_{sum}}\right)$$

where Q_k = runoff forecast for week k

Q_{sum} = cumulative (multiweek) runoff forecast

$\bar{Q}_k$ = long-term runoff mean of week k

$\bar{Q}_{sum}$ = long-term mean of multiweek runoff

MODIFIED ESP METHOD

Efforts to improve forecasts obtained from the Markov model were concentrated on Cedar Inflow Site 1, inflow to the Cedar reservoir. Earlier work on the Cedar River (Lettenmaier et al., 1980) includes streamflow forecasting using the National Weather Service River Forecasting Model (NWSRFM) developed by Burnash et al. (1973) in conjunction with the Snow Accumulation and Ablation Model (SAAM) of Anderson (1973). These are conceptual streamflow and snowmelt simulation models based on temperature and precipitation.

It is expected that more accurate forecasts might be obtainable from a model that includes a representation of the physics of the rainfall-runoff dynamics, rather than a purely statistical based model such as the Markov model. Therefore, it was attempted to incorporate results from the earlier work with the NWSRFM in a simplified Extended Streamflow Prediction (ESP) format.

NWSRFM and SAAM: The snowmelt model calculates the rate of water transfer to the ground (rain plus melt). Runs made for the Cedar River

(Lettenmaier et al., 1980) used four elevation zones to allow adequate representation of varying snow depth with elevation.

The resultant daily rain plus melt records were combined as a weighted average to drive the NWSRF model. This model conceptualizes the infiltration process as a set of five storage reservoirs (Burnash, et al., 1973). Rainfall first enters the upper tension zone that can be emptied only via evaporation. After this is filled, excess water enters the upper storage zone, from which a specified fraction flows into the three lower zones. The lower zone tension water is emptied only via transpiration. The lower zone primary and secondary storages are emptied at two different rates to simulate interflow and base flow recession. The equations describing the drainage rates from each of the zones are given in Burnash, et al. (1973).

Incorporating the NWSRFM and SAAM into a Real-Time Simulation: These models produce satisfactory results when historical data are used (Lettenmaier, 1980). When used in a forecast mode, precipitation and temperature data must be generated to represent future conditions. Usually one of three methods is used: 1) several equally-likely sequences of historical precipitation and temperature are processed and the resulting probability distribution of forecast period runoff is estimated, or, 2) a set of low, average, and high precipitation sequences of specified rank is used and the results assumed to be of the same rank, or 3) a first order variance analysis is performed to define the probability distribution of the resultant flow (Young, et al., 1980). In any case, the method is costly, both in terms of computer dollars and in time spent in data manipulation, and would be cumbersome to incorporate into a real-time simulation model.

To produce a cheaper and more convenient streamflow forecast, a model was developed that regresses future runoff on the storage zone contents. This assumes that the snowmelt and runoff models would be run up to present time, yielding present values of storage zone contents, which would provide the basis for the forecasts. A multivariate stepwise regression model (Draper and Smith, 1966) was applied, using the end-of-week storage zone contents as independent variables, and the forecast period streamflow as the dependent variable. When snow was present in the basin, snow water-equivalent (averaged from the four elevation zones) was also included as an independent variable. Unfortunately, the period of record was limited to 25 years, 1955 to 1980. This is short for statistical tests of its kind, but is typical of the data available in many areas.

The stepwise linear regression model was implemented using a computer subroutine from the International Mathematical and Statistical Library (IMSL). The level of significance for entering and deleting variables in the model was varied from 0.01 to 0.50. The model was also run with the following combination of variables:

1) the contents of all storage zones and snow water-equivalent added together and treated as one variable

2) the contents of all storage zones and snow treated separately

3) The contents of the two tension zones added together, and the remaining zones and snow water-equivalent treated as separate variables

4) the tension zones omitted; the remaining three zones and snow treated as separate variables.

Results: The results (shown in Table 2) showed that tension zone contents were rarely significant in predicting flows, and so were not used. This is apparently because the tension water zones are only emptied by evapotranspiration and do not contribute directly to streamflow.

Transfer rates for the remaining three storage zones are independent of each other and, therefore, best results would be expected when they are treated separately, rather than added together and treated as one variable. This was confirmed by run #4, which gave the best results in terms of percent variance explained by the model. Therefore, this combination of variables was chosen for the model.

The stepwise regression model determines which variables should be included in each week's regression equation. Table 2 shows which variables were accepted at the 0.20 level of significance for the four different forecast periods. It can be seen from this table that none of the storage zone contents were consistently accepted at this level for any extended period of the year or any forecast period. Snow water-equivalent, however, was a good predictor when the forecast period coincided with the ablation season, as would be expected. The forecasts based on the snow-pack improved with increasing forecast period length, in contrast to all of the other variables. The upper free water zone was significant for a few weeks immediately after the snowmelt period for the one and four week forecasts. This is apparently because the water stored in this zone at this time was recent snowmelt, and the contents of this zone served as an extended snow water-equivalent measurement. The lower storage zones were occasionally significant, but not for any reasonable period of time with any consistency.

TABLE 2

Variables Accepted by the Stepwise Regression Model

Significance level for entering and deleting variables = 0.20

WEEK of YEAR \ VARIABLE	SNOW	UZF	LZFP	LZFS	TW	Q (t-1)
0						
1		+			+	+
2			+	▲		▲ ● ■
3		+ ▲	●	●	● ■	● ■
4		●	■	▲ ■	+ ■	+ ■
5	●	▲ ●	▲		+	+ ▲ ■
6		+ ■			+ ■	+ ▲ ● ■
7	● ■	▲ ■	+ ▲	+	+	+ ▲ ●
8			+ ▲	● ■	●	
9	■				+ ▲	+ ▲
10	+		+		▲	
11			+		+	+
12	+					
13		+ ▲			+	+ ▲
14					+	+
15						
16		+	▲		+	+ ▲
17		● ■	● ■		▲	
18		▲		▲	+	+ ▲
19	▲				+	+
20	● ■	▲ ● ■		+ ● ■	●	▲ ● ■
21	● ■				+	▲
22	● ■	▲	+		+	▲ ● ■
23	▲ ● ■				+	▲ ● ■
24	+ ● ■	▲ ● ■	+	+ ▲ ● ■	+ ●	▲ ● ■
25	▲ ● ■	+	+		+ ▲	● ■
26	▲ ● ■	● ■	▲ ●		+ ▲	● ■
27	+ ▲ ● ■	+		● ■	+ ●	+ ▲
28	+ ▲ ● ■			● ■	●	▲
29	▲ ● ■	● ■	▲ ■			+ ●
30	▲ ● ■					+ ■
31	+ ▲ ● ■	+				+
32	+ ▲ ● ■	● ■	● ■			+ ▲
33	+ ▲ ■	▲ ● ■	▲ ● ■	+ ▲ ● ■	●	+ ■
34	+ ▲	▲ ● ■	+ ▲			+ ▲ ● ■
35	+ ▲ ● ■					+ ▲ ● ■
36	+ ● ■	+ ● ■	● ■	▲		+ ▲ ● ■
37	+	▲	▲			+ ▲ ● ■
38	+	+ ▲ ● ■	▲	+		+ ▲ ● ■
39	+ ● ■	+				+ ▲ ● ■
40		▲	▲			+ ▲ ● ■
41	+ ● ■	+ ▲	▲	+ ▲ ● ■	●	+ ▲
42		+		● ■	●	+ ▲
43		▲	▲	+	▲ ■	+ ▲
44		+ ▲	▲	+	■	+ ▲
45			● ■		+ ▲	+
46		▲	▲	+		+ ▲
47		+ ▲	▲			+ ▲
48	▲			▲	+	■
49				▲ ● ■	+ ▲ ● ■	+ ▲ ●
50				+ ● ■	● ■	+ ▲
51		+		+ ▲ ● ■	+ ▲ ●	+
52		▲	+ ▲			+ ▲ ● ■

LEGEND:
Forecast Period
1 wk. +
2 wks. ▲
12 wks. ●
16 wks. ■

The final choice of variables accepted for the streamflow forecast equations is shown in Figure 21. In many cases the model recommended three or more variables to be included for a particular week. Although the forecast variance was usually reduced by adding additional variables, this was considered to be due to multi-colinearity of the supposedly independent variables. The number of variables per equation was, therefore, limited to two.

The only storage zone included is the upper zone free water, and only for four and six weeks, respectively, during the one and four week forecast periods. The coefficients associated with this variable are shown in Table 3. The coefficients show considerable variability: the values for consecutive weeks can vary by over 100 percent and abruptly change from negative to positive.

With the exception of the short period when the upper zone storage entered the forecast equation, the storage zones in the NWSRFM did not prove to be good indicators of future runoff. Snow water storage was a good indicator during the spring and early summer months; however, for most of the year the previous week's runoff was the best indicator of future runoff. The poor forecasting value of the storage zone contents can be attributed to either data limitations or inappropriate model structure, or both.

Three sources of error are associated with the input data, in addition to measurement error. The first is the short record length which can cause excessive statistical variability in the estimated parameters. Due to a lack of long-term meterological records, little can be done to eliminate this source of error. A second source of data error arose because the NWSRF model was calibrated for the portion of the Cedar Watershed above USGS gage 12-1150 (just above Chester Morse Lake), whereas the streamflow forecasts were

Figure 21.

Choice of Variables for Regression Model

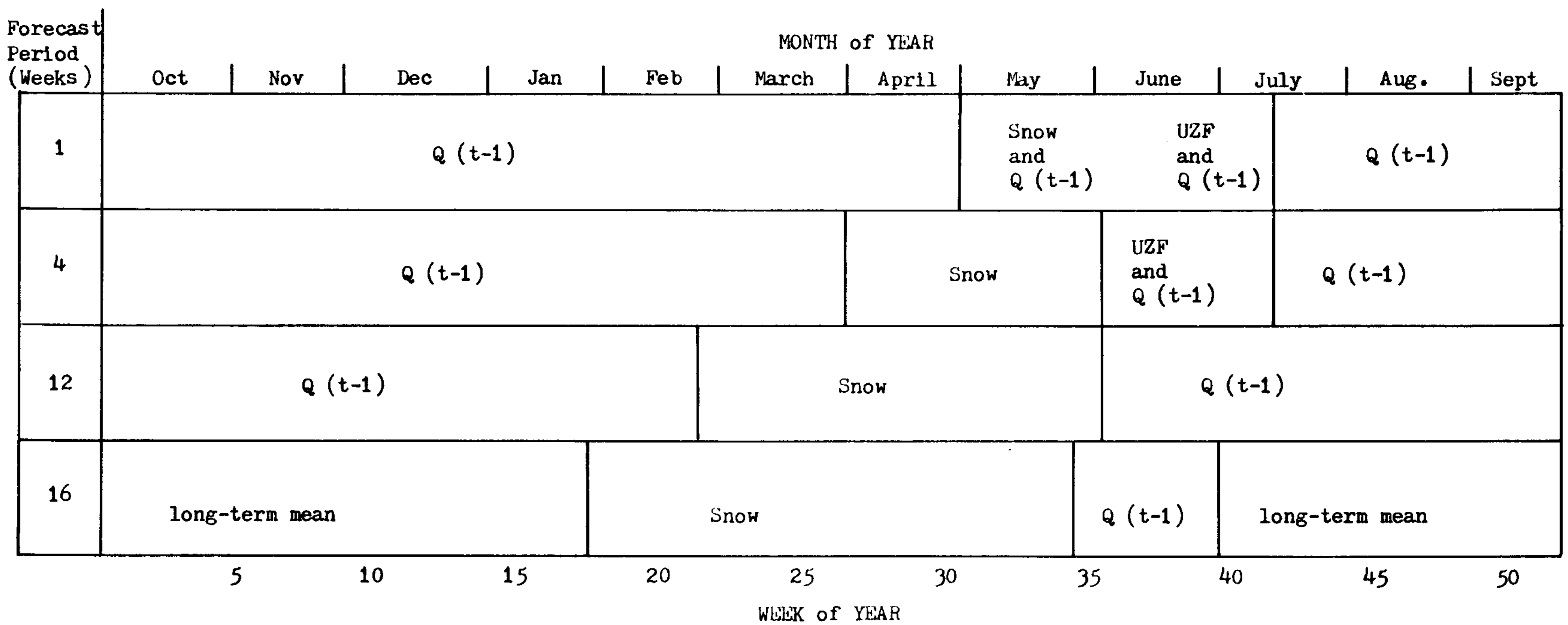


TABLE 3

Coefficients for Regression Model

Forecast Period = 1 Week

Week	UZF[1]	Q(t-1)	B[2]
38	-2862.	0.91	687.2
39	-3298.	1.08	-356.1
40	-1162.	1.07	-996.0
41	6602.	0.35	863.8

Forecast Period = 4 Weeks

Week	UZF[1]	Q(t-1)	B[2]
36	-10065.	3.20	651.
37	4648.	2.28	-137.
38	-10255.	3.21	-539.
39	-8975.	3.46	3316.
40	-3038.	2.76	-1891.
41	12607.	1.12	2577.

[1] UZF = Upper Zone Free Water Contents

[2] Y - Intercept

needed for the Cedar Watershed above the Masonry Pool that includes an additional lower elevation source area. The storage zone contents were, therefore, not entirely representative of the basin for which forecasts were required. The third source of data error was the colinearity of the variables. Although the regression model assumes all variables are independent, this was not always the case for the variables used in the model.

The weak association between storage zone contents and streamflow forecasts displayed by the regression model is also a function of model structure. The model assumes a linear relationship between groundwater storage and future streamflow. This is a defensible assumption when precipitation is low. When forecast period precipitation is high, however, the runoff is a complex function of rainfall and the storage zone contents. The regression model attempts to define a linear relationship based on all precipitation levels, and so it is not surprising that the results are highly variable. Better results could be obtained by dividing the historical record into periods of low, average, and high precipitation. This would result in record lengths too short, however, for valid statistical results.

It was concluded that the results obtained from the modified ESP method did not justify inclusion of the forecasting method into the simulation model. The lag-one Markov model is, therefore, used to make streamflow forecasts for all seven inflow sites. The structure of the model is such that it could easily be modified to allow alternative forecast methods, or, in interactive mode, to incorporate externally generated forecasts.

Chapter 5

MODELING EXAMPLES AND YIELD STUDY RESULTS

EXAMPLES OF INTERACTIVE MODELING

The following examples illustrate how the Cedar/Tolt simulation model can assist in real-time drought management. Illustrations in this chapter are copies of displays that would be seen on a cathode ray tube (CRT) terminal while running the model.

When initiating a modeling session, the user is first given a brief introduction to the model and then asked to define the time frame of the session as shown below. (In all of the following display examples, the user's input is shown in brackets.)

```
************************************************************
*                                                          *
*              CEDAR/TOLT SIMULATION MODEL                 *
*                                                          *
************************************************************

    WELCOME TO THE CEDAR/TOLT SIMULATION MODEL.  THIS MODEL
  SIMULATES OPERATION OF THE SEATTLE WATER SUPPLY SYSTEM,
  INCLUDING THE CEDAR AND TOLT RESERVOIRS, THE NORTH FORK,
  SOUTH FORK, AND MAIN TOLT RIVERS, THE CEDAR RIVER,
  AND LAKE WASHINGTON.  MINIMUM STREAMFLOWS ARE IN EFFECT ON
  THE CEDAR AT RENTON AND ON THE SOUTH FORK TOLT.  YOU WILL
  BE ASKED TO DEFINE ADDITIONAL SYSTEM CHARACTERISTICS AS
  THIS MODELING SESSION PROCEEDS.


 PLEASE ENTER THE INITIAL WATER YEAR OF THE SIMULATION,

 ANY YEAR FROM 1948 TO 1980:
   [1957]

 PLEASE ENTER THE FINAL WATER YEAR OF THE SIMULATION,

 ANY YEAR FROM 1957 TO 1980:
   [1960]

 THE SIMULATION MODEL WILL START IN WATER YEAR 1957
AND END IN 1960.
```

The user is then asked to define certain system characteristics. In the example presented here, the user specified that the City Light Plan is to be in effect and that a diversion dam exists on the North Fork Tolt capable of diverting up to 18,000 AF/month for M & I supply. (Only one of these changes is shown.) The Lake Washington rule curve is assumed to be in effect (requiring natural inflow only), but the 20-foot minimum lake elevation is not enforced. An unusually high base M & I demand of 6500 AF/week is assumed for the purpose of illustrating the model capabilities. The following display illustrates how system characteristics are defined.

```
     YOU NOW HAVE THE OPPORTUNITY TO DEFINE CERTAIN CHARACTERISTICS
OF THE SYSTEM.  LISTED BELOW ARE THE CURRENT MODEL ASSUMPTIONS:
          SYSTEM CHARACTERISTICS:
     1) "CITY LIGHT" PLAN IN EFFECT?                   YES
     2) N. FORK TOLT DIVERSION DAM EXISTS?             YES
     3) LAKE WASHINGTON RULE CURVE IN EFFECT?          YES
     4) LAKE WASHINGTON 20 FT. ELEV. MAINTAINED?       YES
     5) MINIMUM FLOW REQIREMENTS- MAIN TOLT?           YES
     6) BASE M&I DEMAND LEVEL (1000 AF/WEEK)           6.00
     7) SPACE RULE FACTOR                              0.00

WOULD YOU LIKE TO CHANGE ANY OF THESE SYSTEM CHARATERISTICS?
     (Y OR N)
[Y]

     PLEASE ENTER THE NUMBER CORRESPONDING TO THE
SYSTEM CHARACTERISTIC YOU WISH TO CHANGE.
     [6]

PLEASE ENTER THE NEW VALUE DESIRED:
BASE M&I DEMAND IN 1000 AF:
(1981 LEVEL = 2.8, 2025 LEVEL = 4.6)

[6.500000]
```

The user specifies, as shown in this example, that the program is to be run in interactive mode.

```
     YOU NOW HAVE THE CHOICE OF RUNNING THE MODEL IN "INTERACTIVE"
OR "NON-INTERACTIVE" MODE:
     IN INTERACTIVE MODE, THE MODEL PAUSES WHENEVER AN M & I
DEFICIT IS PREDICTED TO OCCUR, AND ALLOWS YOU TO MODIFY
OPERATING POLICIES.
     IN NON-INTERACTIVE MODE, THE MODEL USES PRE-SET OPERATING
POLICIES TO SIMULATE THE SYSTEM OVER THE TIME PERIOD INDICATED
EARLIER.  A SUMMARY OF DEFICITS INCURRED IS PROVIDED.

               FOR INTERACTIVE MODE, ENTER AN I
               FOR NON-INTERACTIVE MODE, ENTER AN N
[I]
```

A brief explanation of interactive mode is then given, and the system simulation begins.

```
     INTERACTIVE MODE:
     THE MODEL WILL START AT THE BEGINNING OF THE SECOND WEEK, AND
MAKE 12 WEEK FORECASTS OF LOW, AVERAGE, AND HIGH FLOWS.  IF
AN M&I DEFICIT IS PREDICTED TO OCCUR WITH THE LOW FORECASTS,
THE MODEL WILL DISPLAY THE PREDICTED DEFICITS.  YOU WILL
THEN HAVE THREE OPPORTUNITIES TO INTERACT WITH THE MODEL:
    1) REQUEST GRAPHICAL DISPLAYS OF PREDICTED RESERVOIR STORAGES,
    2) REQUEST A SUMMARY OF PREDICTED END-OF-WEEK CONDITIONS, AND
    3) CHANGE THE OPERATING POLICY FOR THE CURRENT WEEK.

                 ENTER "RETURN" TO CONTINUE:
```

When a deficit is predicted, the model displays the information as shown below.

```
          CURRENT WEEK = AUG 13, 1958  (WEEK NUMBER   98 OUT OF  208)

  THE FOLLOWING M & I SHORTAGES ARE PREDICTED
TO OCCUR IN THE NEXT 12 WEEKS, FOR THE LOW, AVERAGE AND
HIGH FLOW FORECASTS:      (1000 AF)
```

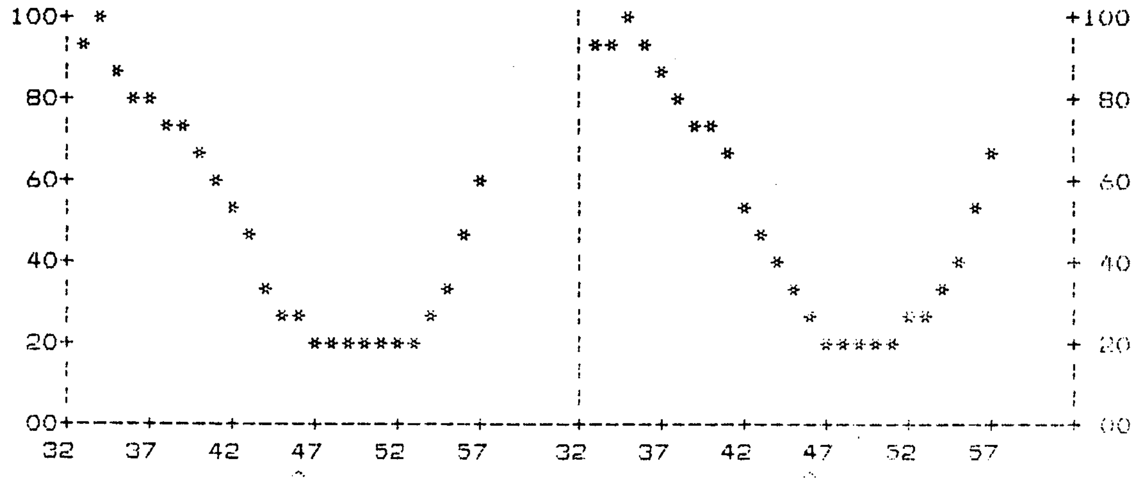
WEEK	LOW	AVE	HIGH
1	0.00	0.00	0.00
2	0.00	0.00	0.00
3	0.00	0.00	0.00
4	0.00	0.00	0.00
5	3.01	0.00	0.00
6	5.88	0.00	0.00
7	6.46	0.00	0.00
8	6.50	3.09	0.00
9	5.29	0.00	0.00
10	6.48	1.68	0.00
11	4.74	0.00	0.00
12	3.88	0.00	0.00

```
[Y]   DO YOU WISH TO INTERACT WITH THE MODEL THIS WEEK?  (Y OR N)
```

In this example, the user next requests a graphical display of predicted reservoir storages for the high, average and low flow forecasts as shown. The forecast period for each of these graphs is 12 weeks, although forecasts of 1, 4, and 16 weeks are also possible. The high flow estimate shows the storage volume decreasing to about 20 percent of capacity for both reservoirs, and then refilling. The average estimate shows the reservoirs being empty at week 50 and M & I deficits (indicated by a dash (-), reaching as high as 40 percent during week 54). The low estimate shows deficits as high as 100 percent. The low and average graphs are stored in memory locations 1 and 2, respectively, for later comparisons.

High Flow Forecast

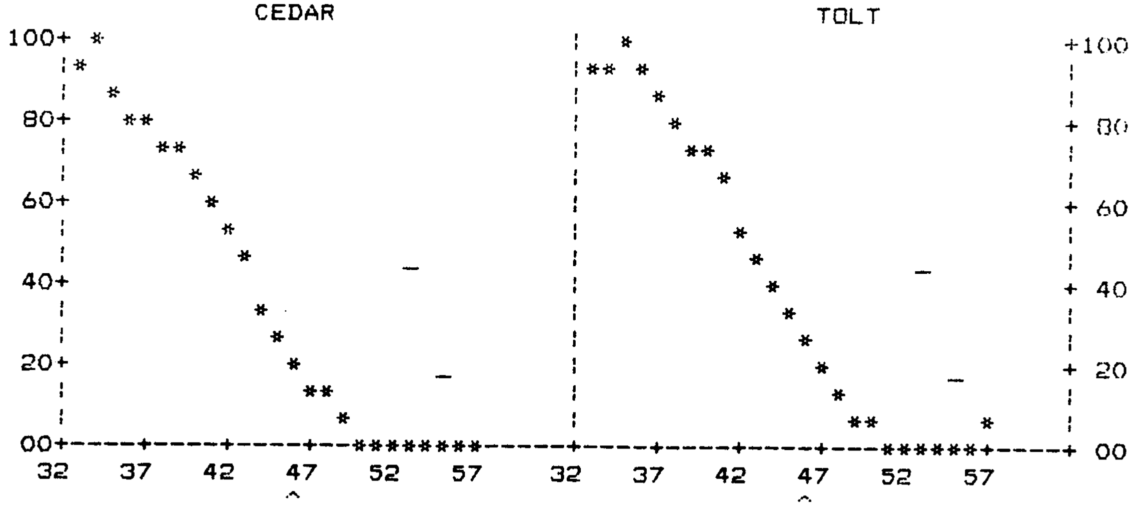
STORAGE (*) IN % OF CAPACITY AND M & I DEFICITS (-) IN % OF DEMAND
FORECAST PERIOD= 12 WEEK(S) FLOW SEQUENCE= HIGH
CEDAR TOLT



WEEK (CURRENT WEEK= 46 (^), AUG 13, 1958)
TO STORE GRAPH, ENTER AN I. D. NO. FROM 1 TO 5; OTHERWISE, ENTER A ZERO:
[3]

Average Flow Forecast

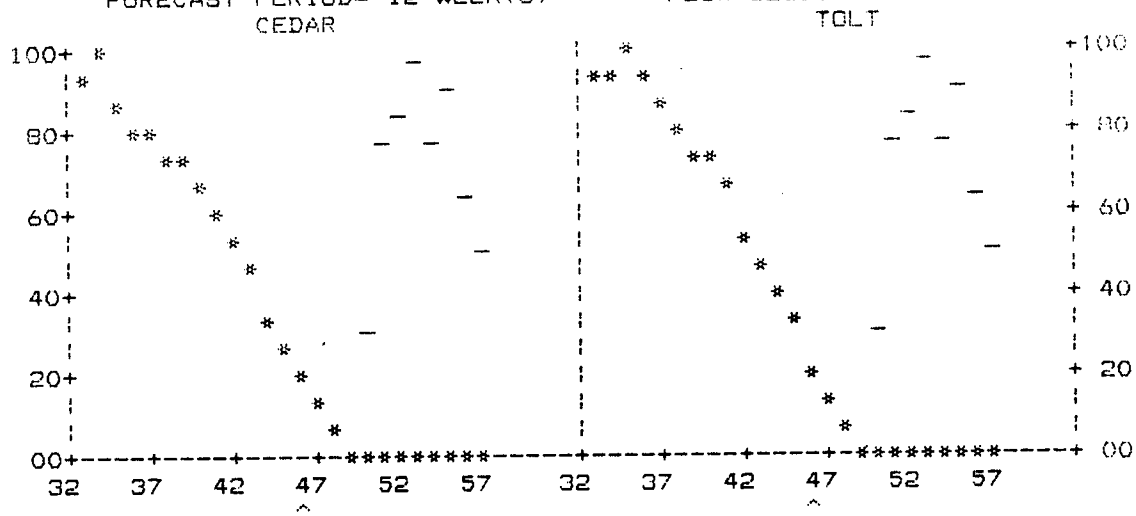
STORAGE (*) IN % OF CAPACITY AND M & I DEFICITS (-) IN % OF DEMAND
FORECAST PERIOD= 12 WEEK(S) FLOW SEQUENCE= AVERAGE
CEDAR TOLT



WEEK (CURRENT WEEK= 46 (^), AUG 13, 1958)
TO STORE GRAPH, ENTER AN I. D. NO. FROM 1 TO 5; OTHERWISE, ENTER A ZERO:
[2]

Low Flow Forecast

STORAGE (*) IN % OF CAPACITY AND M & I DEFICITS (-) IN % OF DEMAND
FORECAST PERIOD= 12 WEEK(S) FLOW SEQUENCE= LOW



WEEK (CURRENT WEEK= 46 (^), AUG 13, 1958)
TO STORE GRAPH, ENTER AN I. D. NO. FROM 1 TO 5; OTHERWISE, ENTER A ZERO:
[1]

The user then is shown a summary of the predicted end-of-week conditions (below). For the week of August 1, 1957, reservoir storage volumes are predicted to range from 14,000 to 15,200 AF in the Tolt reservoir, and from 16,300 to 17,800 AF in the Cedar reservoir, depending on the flow forecast used. The predicted river flows and instream requirements are shown for each river site. An asterik (*) indicates that the requirement is binding; if this requirement were relaxed, additional water could be used for M & I supply or could be stored in the reservoirs. In this case, the Renton, N. Fork Tolt, and Main Tolt requirements are binding for the low flow estimate, whereas the N. Fork Tolt and S. Fork Tolt are binding for the average and high flows.

FOR A SUMMARY OF PREDICTED END-OF-WEEK CONDITIONS AND CURRENT DEMANDS, ENTER A Y.

FOR NO SUMMARY, ENTER AN N.

[Y]

CURRENT WEEK = AUG 13, 1958 (WEEK NUMBER 98 OUT OF 208)

SUMMARY OF PREDICTED END-OF-WEEK CONDITIONS (* MEANS REQ. IS BINDING)

RESERVOIR STORAGES	LOW	AVERAGE	HIGH	CAPACITY
CEDAR (1000 AF)	16.3	16.9	17.8	71.0
TOLT (1000 AF)	14.0	14.5	15.2	56.0

RIVER SITES (1000 AF/WK)	LOW	AVERAGE	HIGH	REQUIRED
RENTON	1.8 *	1.8	1.8	1.8
NORTH FORK TOLT	0.5 *	0.6 *	0.6 *	0.6
SOUTH FORK TOLT	0.5	0.3 *	0.3 *	0.3
MAIN STEM TOLT	1.0 *	1.1	1.3	1.0
RULE CURVE (FT)	21.6	21.6	21.6	21.6
20 FT ELEV. (FT)	21.6	21.6	21.6	0.0
M & I SUPPLY (1000 AF/WK)	10.7	10.7	10.7	10.7

The line labeled "RULE CURVE" indicates the predicted Lake Washington elevation and the rule curve elevation in feet. The line labeled "20 FT. ELEV." again shows the predicted lake levels. The "0.0" under "REQUIRED" indicates that the 20-foot elevation is not being maintained with stored water (a decision made at the beginning of the modeling session).

The predicted M & I supplies and the required volume are shown last. For the current week, M & I supplies are predicted to be adequate regardless of the flow forecasts used.

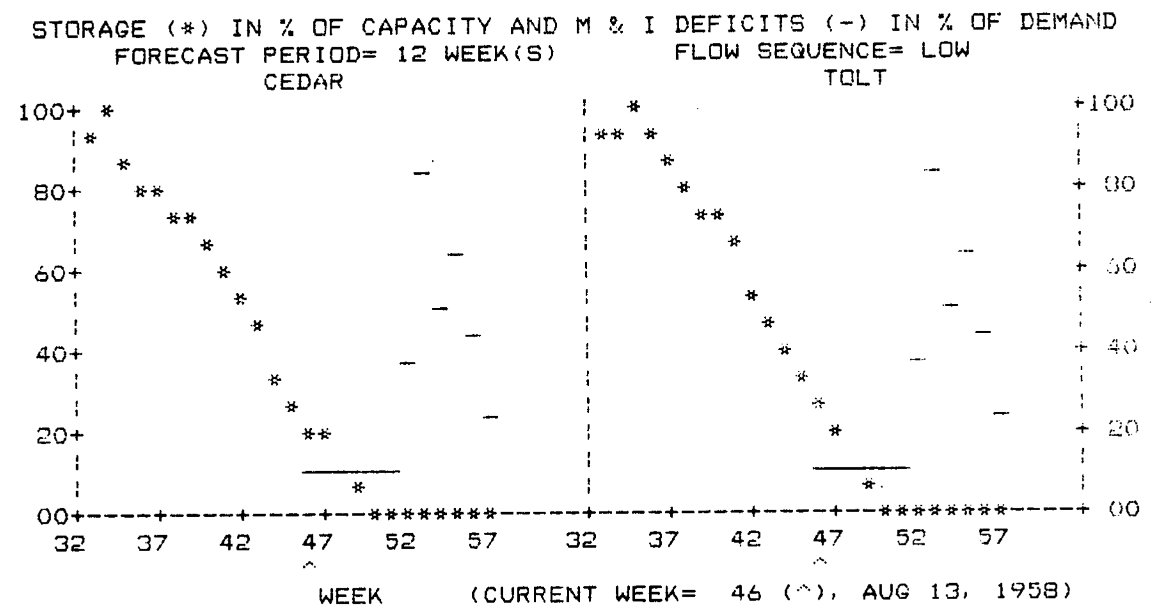
The user then has the opportunity to reduce demands, in order to modify the distribution and severity of the predicted M & I deficits. In this example, three different reduction strategies are evaluated by comparing the new set of predicted M & I deficits to the original predictions in a graphical format.

The first reduction strategy, Plan I, is to reduce all instream requirements by 20 percent and M & I supplies by 15 percent. The previous summary had shown that all instream requirements were binding for at least one flow forecast level, and so a reduction of all sites would be appropriate. This strategy attempted to distribute the shortages fairly evenly between instream requirements and M & I supplies.

```
     WOULD YOU LIKE TO CHANGE ANY DEMANDS FOR THIS WEEK? (Y OR N)
[Y]
     ENTER THE PERCENT REDUCTION (1 TO 100) OF EACH DEMAND UNDER THE
   APPROPRIATE NAME:
   RENTON,   N. F. TOLT,   S. F. TOLT,   MAIN TOLT,   RULE CURVE,   20 FT. ELEV. ,   M&I
[ 20.00000   20.00000     20.00000      20.00000     20.00000       0.00000       15.00000]
```

The resultant storage and deficit predictions for this strategy are displayed next. The deficits resulting from the low forecasts (below) are reduced only slightly from the original predictions. Maximum deficits are reduced from 100% to 85%. The line of dashes shown at the 15% level for weeks 46 - 51 result from the reduction strategy of 15% reduction for M & I requirements, regardless of reservoir storage. This graph is stored in memory location 3.

Low Flow Forecast



TO STORE GRAPH, ENTER AN I.D. NO. FROM 1 TO 5; OTHERWISE, ENTER A ZERO:
[3]

The next display (below) shows the previous graph "overlaid" with the original prediction. The coarse grid size makes the graph somewhat difficult to interpret; this could be improved by using a terminal with a finer grid. The "@" symbols show the reservoir storage volumes for the second memory location indicated (labeled "I.D." on graph) which, in this case, corresponds to reduction Plan I. The "*" symbol shows the reservoir storage value for the first I.D. indicated. When only one symbol occurs, the two storages are approximately equal. The deficits from the first I.D. are shown as (-) and the deficits from the second I.D. are shown as an equal sign (=). In the comparisons shown in this chapter, the first I.D. represents the initial predictions, and the second I.D. represents the deficits resulting from the reduction strategy.

```
     IF YOU WOULD LIKE TO COMPARE TWO GRAPHS, ENTER THE I.D. NUMBER

OF THEIR STORAGE GRAPHS.

     FOR NO COMPARISON, ENTER TWO ZEROS SEPARATED BY A SPACE.
      1          3
```

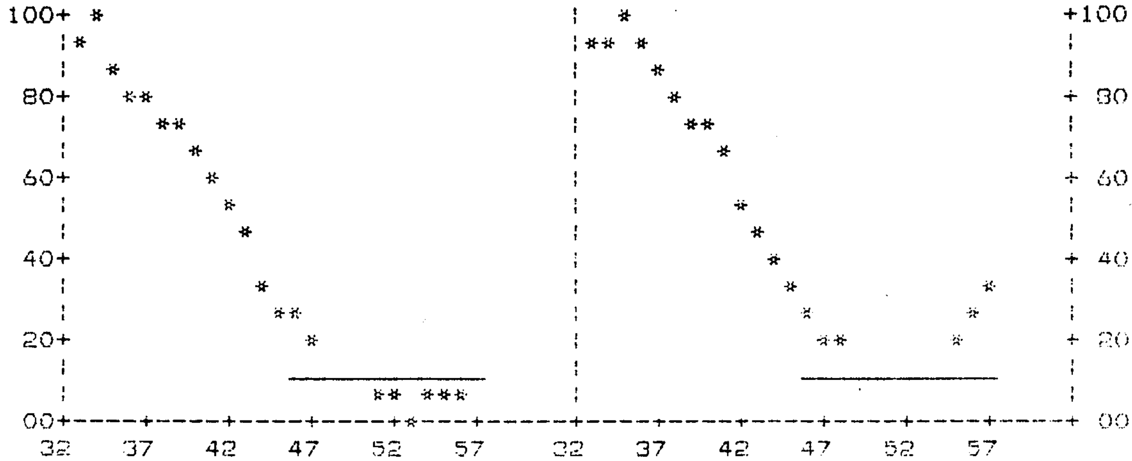
Low Flow Forecast

```
                    CEDAR                                 TOLT
100+ @                        _         !  @                        _         +100
   !@                           _       !@@ @                         _       !
   !  @                      _=         !    @                    _=          !
 80+   @@                  _  _         !     @                 _  _          + 80
   !     @@                             !      @@                             !
   !       @                  =_        !        @                 =_         !
 60+        @                           !                                     + 60
   !         @               =  _       !          @              =  _        !
   !          @                =        !           @               =         !
 40+                       =            !            @           =            + 40
   !            @        _              !             @       _               !
   !             @             =        !              @            =         !
 20+              @@                    !              *@                     + 20
   !              ======                !              ======                 !
   !                *@                  !                *@                   !
 00+----+----+----+-*@@@@@@@@----+----+----+----+----+-*@@@@@@@@----+ 00
  32   37   42   47   52   57   32   37   42   47   52   57
                 WEEK     (CURRENT WEEK=  46, AUG 13, 1958)
  I.D.:       STORAGE:        DEFICIT:     FORECAST PERIOD:    FLOW SEQUENCE:
   1           (*)            (-)          12 WEEK(S)          LOW
   3           (@)            (=)          12 WEEK(S)          LOW
```

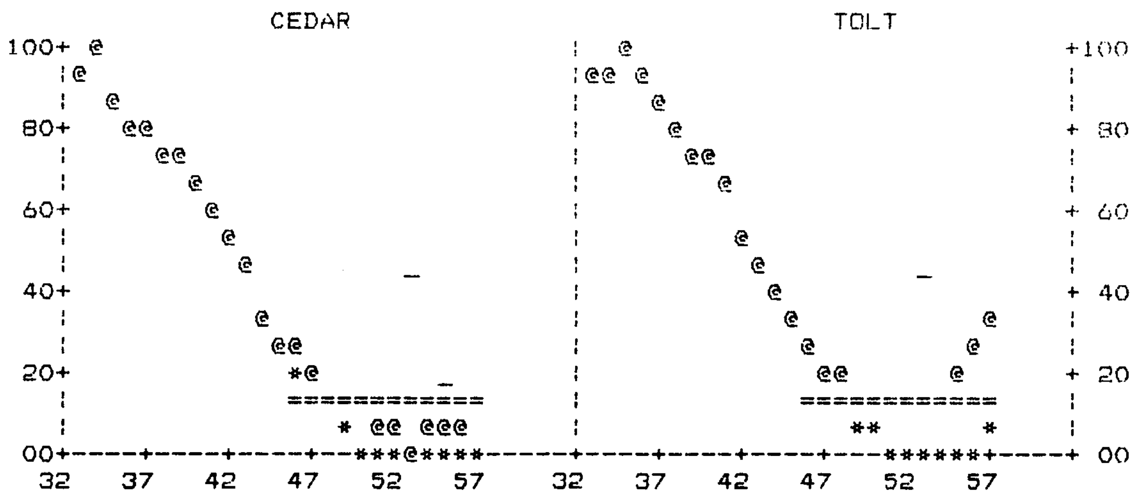
The next graph shows the deficits resulting from the average flow forecasts with reduction Plan I. In this case, deficits in excess of the specified 15% are totally eliminated, although the Cedar reservoir is shown as empty for week 53. Asterisks are overwritten by the deficit symbol when they occur in the same location. The Tolt reservoir storage is seen to dip as low as approximately 15% and then start to refill. The following display shows this graph (I.D. 4) overlaid with the original prediction from the average flow forecasts (I.D. 2). In this case, it is easier to evaluate the two graphs separately than to see them combined into one graph.

Average Flow Forecast

```
STORAGE (*) IN % OF CAPACITY AND M & I DEFICITS (-) IN % OF DEMAND
     FORECAST PERIOD= 12 WEEK(S)        FLOW SEQUENCE= AVERAGE
```




```
                    WEEK      (CURRENT WEEK=  46 (^), AUG 13, 1958)
TO STORE GRAPH, ENTER AN I.D. NO. FROM 1 TO 5; OTHERWISE, ENTER A ZERO:
        [4]
```




```
                    WEEK      (CURRENT WEEK=  46, AUG 13, 1958)
```

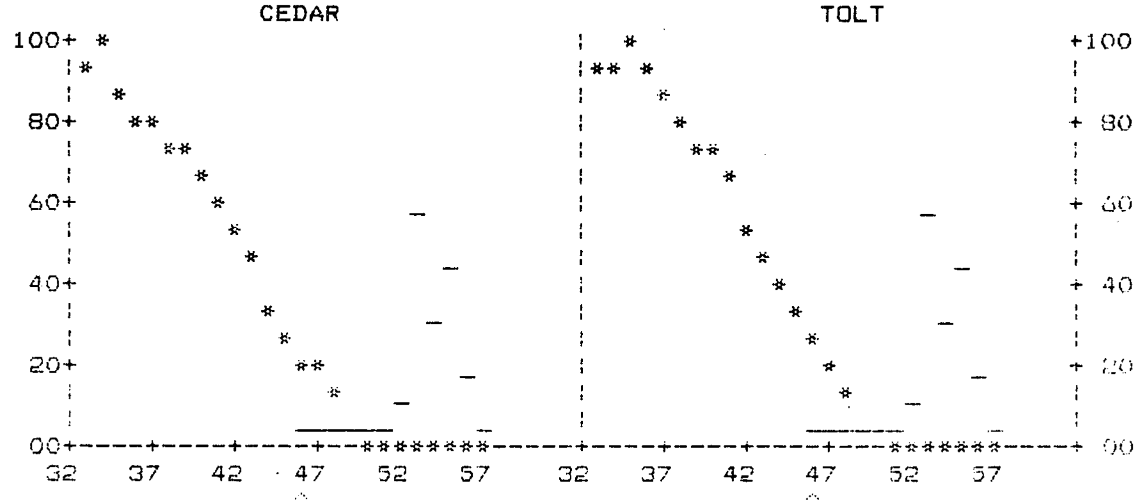
I.D.:	STORAGE:	DEFICIT:	FORECAST PERIOD:	FLOW SEQUENCE:
2	(*)	(-)	12 WEEK(S)	AVERAGE
4	(@)	(=)	12 WEEK(S)	AVERAGE

The second reduction strategy is an attempt to reduce the M & I deficits further. In this case, the instream requirements for the Tolt rivers and the Lake Washington rule curve are totally eliminated, and the Renton and M & I demands are reduced 10% each. The results of these reductions are shown on the following two pages for the low and average flows, respectively. Comparisons with the original predictions are shown below the corresponding graph. In this case, the maximum M & I deficit for the low forecast are reduced to approximately 60%, in comparison to the original 100% predicted. For the average flow forecasts, the reservoir storage does not go below 15% for either reservoir.

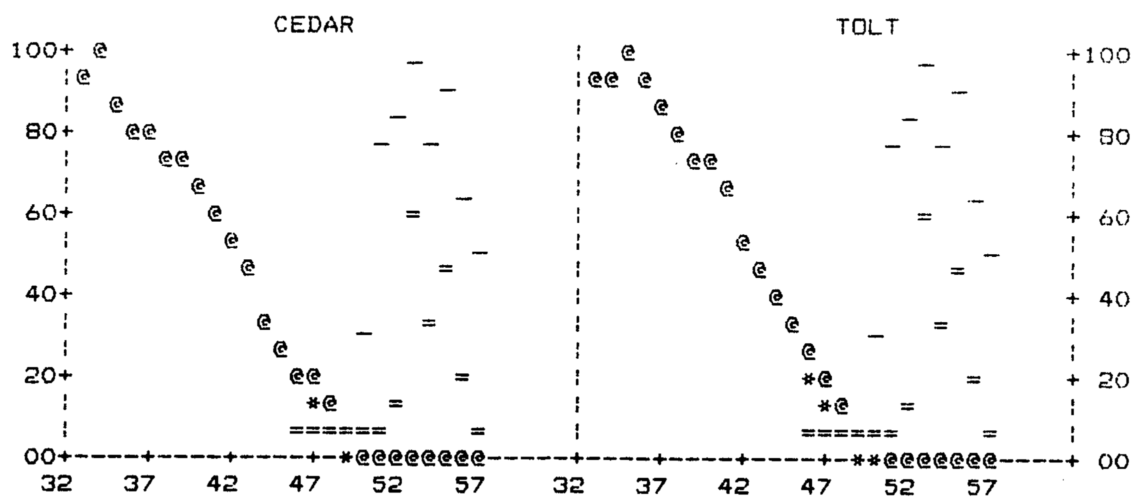
```
     WOULD YOU LIKE TO CHANGE ANY DEMANDS FOR THIS WEEK? (Y OR N)
[Y]
     ENTER THE PERCENT REDUCTION (1 TO 100) OF EACH DEMAND UNDER THE
 APPROPRIATE NAME:
 RENTON,   N.F. TOLT,   S.F. TOLT,   MAIN TOLT,  RULE CURVE,  20 FT. ELEV.,   M&I
[10.00000   100.0000    100.0000    100.0000    100.0000       0.0000     10.00000]


 A NEW SET OF 12 WEEK DEFICIT PREDICTIONS WILL NOW BE MADE
 USING THE NEW DEMANDS YOU HAVE SPECIFIED, AND THE SAME SET
 OF LOW, AVERAGE, AND HIGH FLOWS PREVIOUSLY GENERATED.  YOU
 WILL AGAIN HAVE THE OPTION OF VIEWING PREDICTED STORAGES
 AND MAKING FURTHER CHANGES.
      ENTER  "RETURN"  TO CONTINUE.
```

Low Flow Forecast

STORAGE (*) IN % OF CAPACITY AND M & I DEFICITS (-) IN % OF DEMAND
FORECAST PERIOD= 12 WEEK(S) FLOW SEQUENCE= LOW



WEEK (CURRENT WEEK= 46 (^), AUG 13, 1958)
TO STORE GRAPH, ENTER AN I.D. NO. FROM 1 TO 5; OTHERWISE, ENTER A ZERO.
[5]

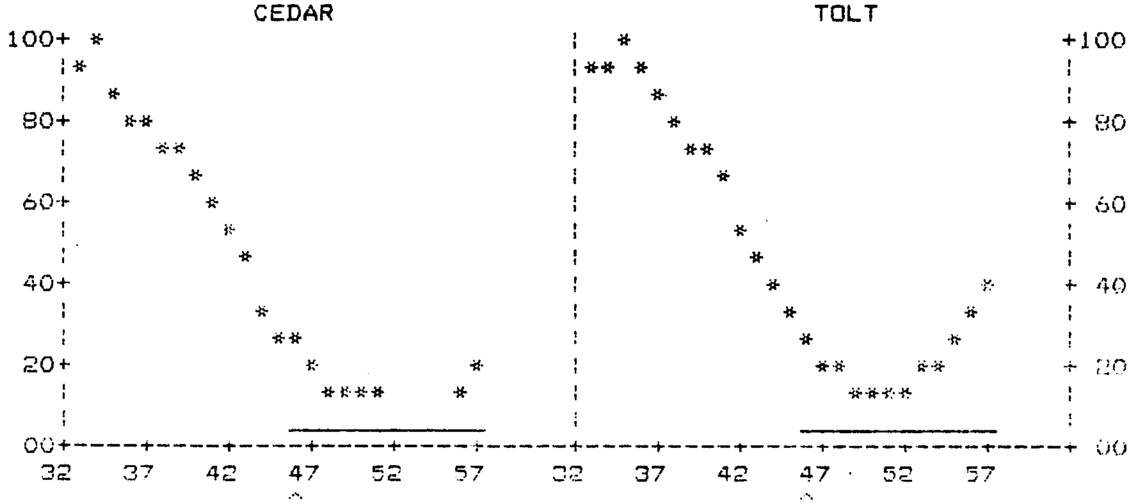


WEEK (CURRENT WEEK= 46, AUG 13, 1958)

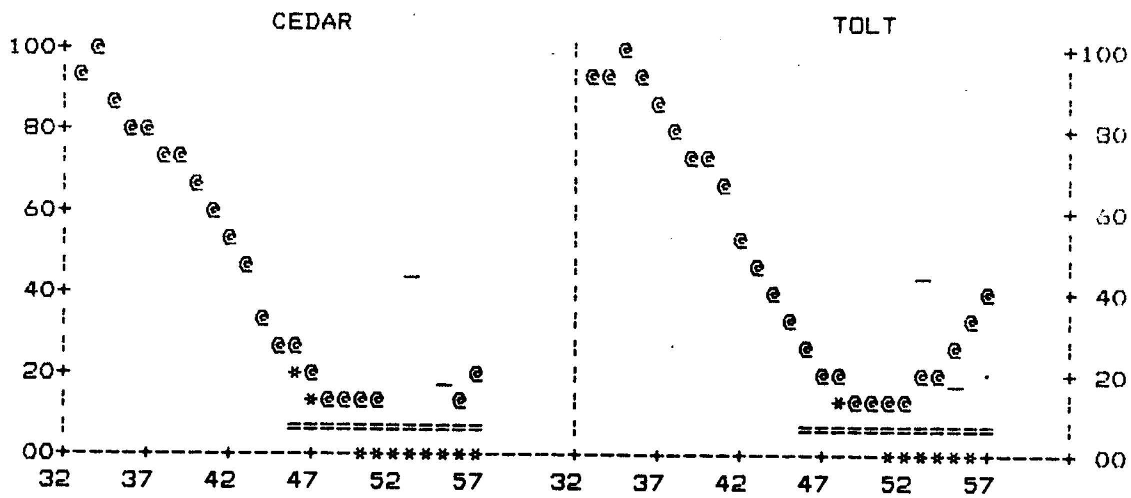
I.D.:	STORAGE:	DEFICIT:	FORECAST PERIOD:	FLOW SEQUENCE:
1	(*)	(-)	12 WEEK(S)	LOW
5	(@)	(=)	12 WEEK(S)	LOW

Average Flow Forecast

STORAGE (*) IN % OF CAPACITY AND M & I DEFICITS (-) IN % OF DEMAND
FORECAST PERIOD= 12 WEEK(S) FLOW SEQUENCE= AVERAGE



WEEK (CURRENT WEEK= 46 (^), AUG 13, 1958)
TO STORE GRAPH, ENTER AN I.D. NO. FROM 1 TO 5; OTHERWISE, ENTER A ZERO:
[4]



WEEK (CURRENT WEEK= 46, AUG 13, 1958)

I.D.:	STORAGE:	DEFICIT:	FORECAST PERIOD:	FLOW SEQUENCE:
2	(*)	(-)	12 WEEK(S)	AVERAGE
4	(@)	(=)	12 WEEK(S)	AVERAGE

The last reduction strategy, Plans III, reduces the Tolt requirements by 60% without reducing any other requirements or M & I demand. The result of this strategy using the average flow forecast is shown below in an overlay with the original predictions. The Cedar Reservoir is empty for weeks 52-57 for this strategy, but no deficits result.

```
      WOULD YOU LIKE TO CHANGE ANY DEMANDS FOR THIS WEEK? (Y OR N)
[Y]
      ENTER THE PERCENT REDUCTION (1 TO 100) OF EACH DEMAND UNDER THE
   APPROPRIATE NAME:
   RENTON,   N.F.TOLT,   S.F.TOLT,   MAIN TOLT,  RULE CURVE,  20 FT. ELEV.,   M&I

   0.0000    60.00000    60.00000    60.00000    0.0000      0.0000         0.0000

                      CEDAR                                   TOLT
  100+ @                                   !  @                                +100
     !@                                    !@@ @                               !
     !   @                                 !     @                             !
   80+    @@                               !      @                            + 80
     !      @@                             !       @@                          !
     !        @                            !         @                         !
   60+         @                           !                                   + 60
     !          @                          !          @                        !
     !           @         _               !           @         _             !
   40+                                     !            @                      + 40
     !            @                        !             @                     !
     !             @                       !              @                    !
   20+              @@       _             !               @      _ @          + 20
     !               *@@                   !                @      @           !
     !                 *@                  !                 @@@@@@@ *         !
   00+----+----+----+--*@@@@@@@----+----+----+----+----+---******+----+ 00
    32   37   42   47   52   57   32   37   42   47   52   57
                     WEEK   (CURRENT WEEK=  46, AUG 13, 1958)
    I.D.:        STORAGE:       DEFICIT:     FORECAST PERIOD:    FLOW SEQUENCE:
     2            (*)            (-)          12 WEEK(S)          AVERAGE
     4            (@)            (=)          12 WEEK(S)          AVERAGE
```

Additional reduction strategies could be investigated in a similar manner. When all desired alternatives have been evaluated, the user decides which reduction strategy is preferred, taking into account the deficits predicted for the forecasting flows and the severity of the reductions. In this example, reduction Plan III is implemented for the current week. The display of deficits resulting from using the actual flows for the week of August 13, 1957 is shown below; as can be seen, all demands were met. All other demands were met. The end-of-week storages are 16,940 AF and 14,510 AF for the Cedar and Tolt reservoirs, respectively.

```
CURRENT WEEK = AUG 13, 1958  (WEEK NUMBER   98 OUT OF  208)
 RESULTS OF USING ACTUAL FLOWS:
```

SITE	DEFICIT (1000 AF)	RESERVOIR	STORAGE	CAPACITY
RENTON	0.00 (0. CFS)	CEDAR	16.94	71.00
N. F. TOLT	0.00 (0. CFS)			
S. F. TOLT	0.00 (0. CFS)	TOLT	14.51	56.00
MAIN TOLT	0.00 (0. CFS)			
LAKE WASH.	0.00 (0.0 FT)			
M & I	0.00 (0 CFS)			

```
        THE MODEL WILL NOW PROCEED TO THE BEGINNING OF THE NEXT
   WEEK AND MAKE A NEW SET OF PREDICTIONS.
        IF YOU WISH TO CONTINUE IN INTERACTIVE MODE, ENTER AN I
[N]     IF YOU WISH TO FINISH THE RUN NON-INTERACTIVELY, ENTER AN N
```

When all weeks of the session are processed (in this case through water year 1960), a deficit summary for the entire session is displayed, as shown below. The system characteristics are also summarized. In this example, the cumulative M & I deficit was 25,750 AF; the average M & I deficit (when one occurred) was 3680 AF/week, and the maximum M & I deficit was 5630 AF/week. A deficit occurred during 7 of the 208 possible weeks. The corresponding information is also shown for each instream and lake level requirement and total deficits. The "TOTAL (LWRC)" label gives the total deficits including the rule curve deficits but not the 20-foot violations, whereas the "TOTAL (LW20')" label is the total for the opposite conditions. In the example shown, the Lake Washington 20-foot violations are zero because that rule is not in effect for this modeling session.

```
                         DEFICIT SUMMARY
               LENGTH OF RUN =   208 WEEKS (1957 - 1960)
      SYSTEM CHARACTERISTICS:

   1) "CITY LIGHT" PLAN IN EFFECT?                    YES
   2) N. FORK TOLT DIVERSION DAM EXISTS?              YES
   3) LAKE WASHINGTON RULE CURVE IN EFFECT?           YES
   4) LAKE WASHINGTON 20 FT. ELEV. MAINTAINED?        NO
   5) MINIMUM FLOW REGIREMENTS- MAIN TOLT?            YES
   6) BASE M&I DEMAND LEVEL (1000 AF/WEEK)            6.50
   7) SPACE RULE FACTOR                               0.00
```

SYSTEM DEMAND	AVERAGE DEFICIT (1000 AF)	MAXIMUM DEFICIT(1000 AF)	CUMULATIVE DEFICIT(1000AF)	NO. OF WEEKS
M & I SUPPLY	3.68 (264. CFS)	5.63 (404. CFS)	25.75	7
LW RULE CURVE	1.94 (0.1 FT)	3.50 (0.2 FT)	50.47	26
LW 20 FT ELEV	0.00 (0.0 FT)	0.00 (0.0 FT)	0.00	0
RENTON REQ.	0.86 (62. CFS)	1.20 (86. CFS)	1.72	2
N. F. TOLT REQ.	0.00 (0. CFS)	0.00 (0. CFS)	0.00	0
S. F. TOLT REQ.	0.00 (0. CFS)	0.00 (0. CFS)	0.00	0
MAIN TOLT REQ	0.30 (22. CFS)	0.93 (67. CFS)	14.27	47
TOTAL (LWRC)	1.44	6.72	92.21	64
TOTAL (LW20')	0.80	6.72	41.74	52

These examples illustrate the use of the Cedar/Tolt model in interactive mode. The following section shows results of the model used as a yield study.

YIELD STUDY RESULTS

Although the Cedar/Tolt simulation model is designed to be used primarily as an interactive tool for drought management, the model can also be used for yield analyses by comparing the deficits resulting from alternative system configurations. As discussed in Draper, et al. (1981), the use of cumulative deficit volumes as indices for system reliability can be a more informative approach to yield analysis than calculating the safe yield for a given set of inflows. Because detailed yield analyses were not considered to be within the scope of this thesis, yield results are presented in this chapter for the purpose of comparing the results to those obtained by Draper, et al. (1981) and discussing the differences in system reliability estimates obtained from the two models.

Table 4 compares deficits resulting from modeling the same system configuration with each model. Deficit results from the weekly model are substantially lower than those from the monthly model. There are two main reasons for these differences:

1) Different Inflow Sequences. The inflow values used by the monthly model were calculated by the Corps of Engineers (1979) by using a regression model to estimate runoff from ungaged areas. The inflow values used by the weekly model were obtained by applying an area proration method (Appendix A) to ungaged areas. Differences in runoff estimates by these two methods can vary substantially. Average annual inflows into the Cedar reservoir estimated by the monthly data averaged ten percent lower than those estimated by the

TABLE 4

Cumulative M & I Deficits for the Period 1948-1975; Comparison of the Monthly and Weekly Models

System Characteristics	Model	M & I Demand (AF/wk)	M & I Deficit (AF)
Present Plan	Monthly	3,700	64,500
	Weekly	3,700	0
	Weekly	4,000	12,680
	Weekly	4,500	66,400
	Weekly	5000	194,440
City Light Plan			
N. Fork Diversion Dam	Monthly	5,100	50,300
	Weekly	5,100	0
	Weekly	5,500	13,700
	Weekly	6,000	49,230
	Weekly	7,000	299,480

1980 demand = 2,800 AF/wk
2000 demand = 4,000 AF/wk
2025 demand = 5,100 AF/wk

weekly data. The impact of these differences on deficit predictions is illustrated by the autumn 1952 drought which resulted in an M & I deficit of 35,000 AF when modeled with the monthly model (with a base M & I demand of 5.08 AF/wk), but resulted in no M & I deficits when modeled with the weekly model. Inflow estimates for water year 1952 were 35,600 AF (13 percent) greater for the monthly model than the weekly model. The difference in inflow estimates could account for a large portion of the deficit prediction difference.

2) Weekly Time Step. The weekly time step allows operating policies to be closely suited to the actual conditions. A monthly time step results in defining operating policies based on system conditions up to four weeks earlier, which may not be appropriate for current conditions. This is especially important for defining minimum flow requirements. The difference between the normal and critical instream requirements are considerable, and can easily account for large differences in deficit projections.

The weekly data were prepared for the period 1948 through 1980 because daily records were not available before that time. Unfortunately, this period does not include the droughts of the 1930's and 40's which were more severe than those occurring after 1948. Therefore, a "safe yield" (no deficit occurring with the flow sequence used) as computed by the weekly model does not take into account the full range of historical conditions.

Despite this limitation, the results obtained by the weekly simulation model show that the Cedar/Tolt system may be better able to meet future M & I demands than was previously estimated. The present system configuration was shown (Table 4) to reliably provide approximately 1.3 times the current base M & I demand of 2.8 AF/wk. With the City Light Plan and the

North Fork diversion dam, the system was shown to provide the year 2025 demand of 5.08 AF/wk with no M & I deficits. These results, however, are dependent on the accuracy of the inflow data and are based only on the period 1948 to 1980. Reestimating these values with more precise methods and extending the time frame to include earlier years is needed to confirm the reliability estimates of the weekly simulation model.

Chapter 6

SUMMARY AND CONCLUSIONS

SUMMARY

The primary purpose of the Cedar/Tolt simulation model is to facilitate real-time drought management. A secondary purpose is to provide an efficient method for evaluating system yield given a sequence of inflows. The model represents several improvements over previous modeling efforts for the Cedar/Tolt System, including:

1) Weekly Time Step: Previous models have used a monthly time step, largely because some of the historic inflow data were not available on a shorter time scale. Unfortunately, a monthly time step is too long for simulation of realistic operating policies. Re-estimation of local inflow data, as described in Appendix A, was undertaken to upgrade the data base for the period 1948-80 to a weekly time interval.

2) Streamflow Forecasts for a Range of Risk levels: The model provides streamflow forecasts for the 10, 50, and 90 percentile flows for all inflow sites. This allows the user to assess the deficit risks associated with alternative operating policies.

3) Interactive Capability: The most important advance represented by the model is its interactive nature that allows the user to modify and evaluate operating policies during the course of a simulation run. The interactive capabilities also provide a more convenient display format for evaluating system performance.

MODEL ASSESSMENT

The Cedar/Tolt model can be evaluated with respect to three criteria: 1) simulation accuracy, 2) forecasting accuracy, and 3) interactive capabilities.

Simulation Accuracy: Simulation accuracy depends on the validity of certain simplifying assumptions and on the accuracy of the input data. These are briefly discussed below:

a) Local inflow values: The historical weekly inflow values were compiled from daily streamgage records when available; otherwise from monthly inflow values previously estimated by the Corps of Engineers (Appendix A). Because some of the inflows are estimated by difference rather than directly from gage information, the accuracy of these historical inflows is questionable; it is expected that the weekly values may be in error by as much as 20 percent. If the errors are mainly due to measurement variability, they will tend to cancel each other somewhat when the model is used for long-term yield determinations. When analyzing specific droughts, however, the inflow inaccuracy could significantly affect model results. If the inflow estimates are significantly biased, yield analysis results would definitely be affected. In addition, conclusions as to which instream or lake level requirements are binding could also change.

b) Conceptualization: The Cedar/Tolt model conceptualizes the system as a series of reaches. Within each reach there is assumed to be no evaporation, groundwater contribution, diversions other than the two modeled, or inflow except at the beginning of the reach. These assumptions do not significantly affect the accuracy of the system.

c) Seepage: The seepage equations used in the model are based on equations derived from water balance studies on the Cedar reservoir (U.S. Army Corps of Engineers, 1980). This method estimates seepage by difference and, therefore, incorporates the uncertainty of all other terms into the calculated seepage volume. In addition, representation of the groundwater system as a simple underground reservoir of specified capacity is a major over-simplification of the real system. The lag time of return seepage and the fraction of water lost to the Snoqualmie River are variable quantities, but the model assumes them to be constant. Additional research on groundwater behavior near the Cedar reservoir is necessary to model this aspect of the system more accurately.

d) Lake Washington: The largest source of error associated with Lake Washington is in estimating lockage flow, a function of marine traffic. The model assumes that lockage flow is equal to the historical weekly average or, during drought conditions, to natural inflow. During severe drought conditions, the Corps of Engineers (the agency responsible for lockage operations) may decide to reduce lockage flow further by limiting the number of lockages, which would reduce the demand for Cedar River inflow to Lake Washington. The lockage flows can, therefore, affect the results of the simulation yield and Lake Washington deficits. This could be modified by adding a set of decision rules for lockage flow reduction during drought conditions.

e) Operating policies: The interactive capabilities and the weekly time step allow realistic simulation of operating policies, in contrast to earlier models on a monthly time step.

The accuracy of the model can be concluded to be limited primarily by local inflow, seepage, and lockage outflow estimates. The sensitivity of the model results to these parameter estimates could be analyzed by noting the change in system yield for incremental changes in parameter estimates.

Forecast Accuracy: The value of forecasts provided by the lag-one Markov equation is a function of the correlation between the forecast period and previous week's streamflow. When the correlation coefficient is low (generally the case in the winter), the 50 percentile forecast is essentially equal to the long-term mean. During the summer and early fall when the correlation coefficient is higher, more accurate forecasts result.

Interactive Capabilities: Advantages of the interactive nature of the model include:

a) Flexibility: The user can modify system characteristics and operating policies easily.

b) Informative displays: The model identifies binding constraints, provides plots of reservoir storages, and summarizes system reliability in graphical and tabular displays.

c) Multiple Uses: In addition to drought management and yield determinations, the model can be used as a communication aid for non-technical users. For example, the model can be used to illustrate to agencies with potentially conflicting objectives (such as the Corps of Engineers, Department of Fisheries, and Seattle Water Department) the impacts of various operating policies. This would be especially useful when negotiating the instream requirements to be in effect under drought conditions.

There are several limitations in the current formulation of the model. Some of these are a result of the constraints of a standard 26 by 80 CRT terminal, which limits the resolution of the graphics. For example, the "overlay" technique used to compare two graphs (described in Chapter 3) can sometimes result in a display that is difficult to interpret. Space also limits the ability to provide clear labels, explanations, or instructions in some cases.

Interactive capabilities are limited in certain instances. For example, it is not possible to reduce lockage flow to less than natural inflow, or to require specific releases from the reservoirs. A further limitation of the interactive capability occurs when the user is evaluating alternative operating policies. When a demand reduction is specified, new deficit forecasts are calculated based on that reduction being in effect for the entire forecast period, even if it is not always necessary. This can result in over-estimates of forecasted deficits. This limitation only occurs in the forecast mode, however; when actual weekly flows are used, demand restrictions are in effect for the current week only.

In general, the interactive capabilities are flexible enough to allow realistic simulation of the system.

RECOMMENDATIONS FOR MODEL IMPROVEMENTS

A major limitation of the model is that it does not identify an optimum operating policy. A useful addition to the model would, therefore, be inclusion of an optimization subprogram. A linear program could be incorporated to define the optimum operating policy for the forecast period (up to 16 weeks), based on an objective function defined for the system. Ideally, the objective function would be interactive, allowing comparison of strategies resulting from alternative priority definitions. An optimization subprogram would allow the user to evaluate the costs (not necessarily in dollar terms) of non-optimal policies.

It is also recommended that a data updating program be added, so that the model can be used as a real-time tool more easily. The current version of the model requires weekly inflow volumes at seven sites. A subprogram could be added to compute inflow estimates based on a selected number of weekly stream gage readings.

Finally, it is recommended that alternative streamflow forecasting methods be investigated to provide more accurate deficit predictions during severe droughts. Results obtained from the modified ESP method described in Chapter 4 did not justify inclusion in the model. Alternative methods, such as those based on basin storage accounting, or conceptual simulation, could improve forecasting accuracy. The increased computational costs of more complex methods would be justified whenever the system is faced with severe shortages. The simpler lag-one Markov model is adequate for normal conditions. The modular structure of the model allows the forecasting subprogram to be easily modified or replaced.

CONCLUSIONS

Interactive simulation models represent an alternative management technique. This modeling approach has the potential for improving management policies beyond those based on rigid operating rules. In addition, interactive simulation modeling allows the impacts of alternative operating policies to be evaluated directly. As interactive computers become more accessible to water resource managers, this approach is expected to become an integral part of the management process.

Yield analyses performed with the weekly Cedar/Tolt simulation model show that the present system can reliably provide M & I supplies up to approximately 1.3 times the current base demand of 2.8 AF/wk. With the City Light Plan in effect and a diversion dam on the North Fork Tolt, the system could reliably provide the year 2025 demand of 5.08 AF/week. These results, however, are based on the historical flows of 1948 through 1980, and do not include the considerably drier years of 1930 through 1948. Therefore, the results should be considered to be upper bounds for reliability estimates.

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Appendix A

INFLOW DATA PREPARATION

Weekly inflow volumes were compiled for the seven inflow sites shown in Figure 4 for the period October 1, 1947 through September 31, 1980 (water years 1948-1980). The initial data available consisted of the following:

- Monthly inflows at all sites estimated by the U.S. Army Corps of Engineers (COE, 1979) for the period 1929-1975.
- Daily diversion records for the Landsburg site for 1976-1980.
- Daily stream gage records for the following sites and dates:

USGS Gage No.	Site Name	Dates (water years)
12-1150	Cedar R. at Cedar Falls	1948-80
12-1155	Rex River	1948-80
12-1170	Taylor Creek	1957-80
12-1175	Cedar R. at Landsburg	1948-80
12-1190	Cedar R. at Renton	1948-80
12-1475	S. Fork Tolt at Carnation	1953-63, 69-80
12-1476	N. Fork Tolt	1961-63, 69-80
12-1480	S. Fork Tolt at Carnation	1953-63, 70-80
12-1485	Main Tolt at Carnation	1948-80

Three approaches were used to estimate the desired weekly inflows, depending on the type of initial data available for the site:

1) Daily Method When the appropriate daily streamflow records were available, these were simply added together to give weekly flows at the gaged site. Each year consists of 52 weeks and either one (normal year) or two (leap year) extra days. One extra day was added to a week during the spring melt period (week 30, April 22-29) under the assumption that this would be unlikely

to be a critical (drought) week. The extra day for leap year was added to week 22 (Feb. 26-March 3) during leap years.

This aggregate method provided weekly flows at the gage sites. Most inflow areas, however, included a large portion of ungaged areas. When a gage site was located both above and below the river reach in question and diversion data were available, the local inflow was found by difference. In other cases, a runoff coefficient was determined for the ungaged areas, based on studies by Howard (1978), and the U.S. Army Corps of Engineers (COE, 1979).

2) Monthly Disaggregation Method When insufficient daily flow records were available, the monthly inflow estimates were disaggregated into daily flows by copying the daily pattern from a nearby gage ("master gage"). If only one gage existed within a reasonable distance, it was chosen to be the master station; otherwise, the station with the highest correlation between the two streamflows (as measured by the correlation coefficient) was chosen. After the daily pattern was established, the daily flows were aggregated to weekly as in the Daily Method described above.

3) Variance Method In a few instances, neither monthly nor daily records existed for a site (for example, Lake Washington Inflow, 1976-80). In these cases, the missing inflow data was assumed to be the same number of standard deviations above or below the mean as a nearby station.

The methods used for each site are described below. The symbol QXXXX indicates streamflow at USGS gage 12-XXXX.

Cedar Inflow 1

Inflow to the Cedar reservoir was estimated according to the relationship defined by Howard (1978):

Cedar Inflow 1 = 1.412 x Q1150 + 1.782 x Q1155

Daily records existed for both stations for the entire time period needed.

Cedar Inflow 2

Inflow to the Cedar between the reservoir and Landsburg was estimated according to (Howard, 1978):

Cedar Inflow 2 = 2.111 x Q1170

Daily records were available for 1957-80. For the period 1948-1956, the Monthly Dissaggregation Method was applied with USGS 12-1175 used as the master station.

Cedar Inflow 3

The Monthly Disaggregation Method was used for the period 1948-1975 with USGS 12-1190 as the master station. From 1976-1980 the following relationship was used on daily data aggregated to weekly:

Cedar Inflow 3 = Q1190 - Q1175 + Landsburg Diversion

North Fork Tolt Inflow

The Monthly Disaggregation Method was used for the period 1948-52 and 1964-68 with USGS 12-1485 used as the master station. Daily data existed for the remaining water years allowing the inflow to be calculated according to:

North Fork Tolt Inflow = Q1475

South Fork Tolt Inflow

The Monthly Disaggregation Method was used for the period 1948-60 and 1964-68 using USGS 12-1485 as the master station. Daily data was used for the remaining years according to:

South Fork Tolt Inflow = 3.0 x Q1476

Main Stem Tolt Inflow

The Monthly Disaggregation Method was used for the period 1948-52 and 1964-69 with USGS 12-1485 as the master station. Daily data was used for the remaining years according to:

Main Tolt Inflow = Q1485 - Q1480 - Q1475

Lake Washington Inflow

Lake Washington inflow was estimated by the Monthly Disaggregation Method for the period 1948-1975 with USGS 12-d1190 used as the master station. Inflow for 1976-80 was estimated by the Variance Method, also using USGS 12-1190 as the master station.

Appendix B

Subroutine System

```
      SUBROUTINE SYST(IWEEK,N,IRANK,CHANGE)
      COMMON/COM1/CAPC1(52),CAPC2(52),CAPT1(52),DEM(52),
     + OUTLOCK(52)
      COMMON/COM4/KCITY,KDIV,KELEV,KLAKE,KMAIN,DSYS,SFAC,CAPC,CAPT,
     + STORET(1740),STOREC(1740),DEFTOT(7,1740),BIND(6,1740)
      COMMON/COM6/INFLOW(7,1740)
        COMMON/COM3/REQR,REQL,REQN,REQS,REQM,XBIND(6,3),STOREL(1740),
     + SUMM(8,3),REQE
        DIMENSION CHANGE(7),  QPRED(7,3,16)
        REAL INFLOW,INC1,INC2,INC3,INT1,INT2,INT3,INL

        CAPNF = 18.0/4.33
        CAPLAND = 18.0/4.33
        STOREL(1)=486.2
        IF(IRANK.NE.0) CALL PREDICT(N,IWEEK,QPRED)
      JWEEK =IWEEK+N-1
      JJ=0

      DO 1001 I=IWEEK,JWEEK
      II=MOD(I,52)
      IF(II.EQ.0) II=52
      K=I-1
        DO 5 KK=1,6
        BIND(KK,I)=0.0
5       CONTINUE

      IF(IRANK.EQ.0) THEN
C       DO 3 KK=1,7
C       IF(INFLOW(KK,I).LT.0.0) INFLOW(KK,I)=0.0
C3      CONTINUE
        INC1 = INFLOW(1,I)
        INC2 = INFLOW(2,I)
        INC3 = INFLOW(3,I)
        INT1 = INFLOW(4,I)
        INT2 = INFLOW(5,I)
        INT3 = INFLOW(6,I)
        INL  = INFLOW(7,I)
      ELSE IF(IRANK.NE.0) THEN
        JJ = JJ + 1
        INC1 = QPRED(1,IRANK,JJ)
        INC2 = QPRED(2,IRANK,JJ)
        INC3 = QPRED(3,IRANK,JJ)
        INT1 = QPRED(4,IRANK,JJ)
        INT2 = QPRED(5,IRANK,JJ)
        INT3 = QPRED(6,IRANK,JJ)
        INL  = QPRED(7,IRANK,JJ)
      ENDIF

        IF(KCITY.EQ.2) CAPC=CAPC1(II)
        IF(KCITY.EQ.1) CAPC=CAPC2(II)
        CAPT=CAPT1(II)

      CALL REQUIRE(I,KDIV,KELEV,KLAKE,KMAIN,REQR,REQN,REQS,REQM,REQL,
     + REQE)
      XSYS=DSYS*DEM(II)

        REQR = REQR - REQR*CHANGE(1)/100.
```

```
        REQN = REQN - REQN*CHANGE(2)/100.
        REQS = REQS - REQS*CHANGE(3)/100.
        REQM = REQM - REQM*CHANGE(4)/100.
        REQL = REQL - REQL*CHANGE(5)/100.
        REQE = REQE - REQE*CHANGE(6)/100.
        XSYS = XSYS - XSYS*CHANGE(7)/100.

C TOLT SYSTEM CALCULATIONS
C      FIRST CALCULATE FLOW IN THE SOUTH FORK TOLT ("FLOWS")
      IF(INT2+STORET(K).LE.REQS) THEN
        FLOWS = INT2 + STORET(K)
      ELSE
        FLOWS = REQS
      ENDIF

C  MEET MAIN STEM REQUIREMENTS IF POSSIBLE, USING STORED WATER IF
C  NECESSARY
      FLOWM = INT1+INT3+FLOWS
      IF(FLOWM.LE.REQM) THEN
        FLOWS=AMIN1(REQM-INT1-INT3,INT2+STORET(K))
        FLOWM=INT1+INT3+FLOWS
      ENDIF

C  IF THERE IS ANY EXCESS N.F. WATER, DIVERT IT:
      IF(FLOWM.GT.REQM.AND.INT1.GT.REQN.AND.KDIV.EQ.1)
     + THEN
C        (NREQM=N.F. WATER NEEDED TO MEET MAIN STEM REQUIREMENTS)
        NREQM=AMAX1(REQM-FLOWS-INT3,0.0)
        EXCESSM=INT1-NREQM
        EXCESSN=INT1-REQN
        DIVN=AMIN1(EXCESSM,EXCESSN)
        IF(DIVN.LE.0) DIVN=0.0
        IF(DIVN.GE.CAPNF) DIVN=CAPNF
        IF(DIVN.GE.XSYS) DIVN = XSYS
        FLOWN=INT1-DIVN
        FLOWM=FLOWS+FLOWN+INT3
      ELSE
        FLOWN=INT1
        DIVN=0.0
      ENDIF

C  DETERMINE WHICH REQUIREMENTS ARE BINDING, IF ANY:
        IF(FLOWN.LE.REQN.AND.REQN.GT.0) BIND(4,I)=1
        IF(FLOWS.LE.REQS.AND.REQS.GT.0) BIND(5,I)=1
        IF(FLOWM.LE.REQM.AND.REQM.GT.0) BIND(6,I)=1

C  CEDAR SYSTEM
C  CALL SEEPAGE SUBROUTINE TO CALCULATE SEEPAGE LOSS AND RETURN:
      CALL SEEPS(STOREC,SEEP,RSEEP,K,I,KCITY)
      DIVLAND=0.0
      DRAFT=0.0

        DRAFT1 = 0
        DRAFT2 = 0
        DRAFT3 = 0

C  DRAFT NEEDED FOR RENTON REQUIREMENTS:
```

```
      FLOWR = RSEEP + INC2 + INC3
      IF(FLOWR.LT.REQR) DRAFT1 = AMIN1(INC1,REQR-FLOWR)
      IF(DRAFT1.LT.0.) DRAFT1=0.0

C  DRAFT NEEDED FOR LAKE WASHINGTON RULE CURVE:
      SALT=AMAX1(0.   ,0.00898*(STOREL(K)-442.0) - 0.1208)
      FLOWOUT = OUTLOCK(II) + SALT
      FLOWIN = FLOWR + INL
      XSTOREL = STOREL(K) + FLOWIN - FLOWOUT
      IF(XSTOREL.LT.REQL) THEN
        FLOWNAT = INC1 + INC2 + INC3 + INL
        IF(FLOWOUT.GT.FLOWNAT) FLOWOUT = FLOWNAT
        XSTOREL=STOREL(K)+FLOWIN-FLOWOUT
        IF(KLAKE.EQ.1) DRAFT2 = AMIN1(FLOWOUT-FLOWIN,REQL-XSTOREL)
        IF(DRAFT2.LT.0.0) DRAFT2 = 0.0

C  DRAFT NEEDED TO KEEP ELEVATION ABOVE 20 FEET:
        AVAIL = AMAX1(0.  ,  STOREC(K) + INC1 - SEEP)
        IF(XSTOREL.LT.REQE.AND.KELEV.EQ.1)
     $     DRAFT3 = AMIN1(AVAIL,REQE-XSTOREL)
          IF(DRAFT3.LT.0.0) DRAFT3 = 0.0
      ENDIF

C  FIND THE MAXIMUM OF THE 3 DRAFTS (THE BINDING REQUIREMENT):
      DRAFT=AMAX1(DRAFT1,DRAFT2,DRAFT3)
      IF(DRAFT.GT.0.) THEN
        IF(DRAFT.EQ.DRAFT1) BIND(1,I) = 1
        IF(DRAFT.EQ.DRAFT2) BIND(2,I) = 1
        IF(DRAFT.EQ.DRAFT3) BIND(3,I) = 1
      ELSE
        DIVLAND = AMAX1(0.,FLOWR-REQR)
        IF(DIVLAND.GT.XSYS) DIVLAND = XSYS
      ENDIF

C  UPDATE STORAGE IN RESERVOIRS AND UNMET DEMAND
10    XSTORET=STORET(K)-FLOWS+INT2
      XSTOREC=STOREC(K)-SEEP-DRAFT+INC1
        IF(XSTOREC.LT.0.0) THEN
          DRAFT = DRAFT + XSTOREC
          XSTOREC = STOREC(K) - SEEP - DRAFT + INC1
        ENDIF
      XSYS=XSYS-DIVN-DIVLAND
      IF(XSYS.LT.0) DIVLAND = AMAX1(0.,DIVLAND+XSYS)

C  IF DEMAND IS MORE THAN TOTAL AVAILABLE, USE ALL WATER
C  IF UNMET DEMAND IS ZERO, THEN DRAFT IS ZERO
C  OTHERWISE, CALL 'SPACE' FOR ALLOTMENT DECISION
        IF((XSTOREC + XSTORET).LE.XSYS) THEN
        DIVC=XSTOREC
        DIVS=XSTORET
      ELSEIF(XSYS.LE.0) THEN
        DIVC=0.0
        DIVS=0.0
      ELSE
        CALL SPACE(XSTOREC,XSTORET,XSYS,I,II,DIVS,DIVC,CAPC,CAPT,SFAC)
      ENDIF
```

```
C  UPDATE STORAGE AND FLOWS:
      STOREC(I)=STOREC(K)+INC1-SEEP-DRAFT-DIVC
      IF(STOREC(I).LE.0.) STOREC(I)=0.
      IF(STOREC(I).GE.CAPC) STOREC(I)=CAPC
      DRAFT=STOREC(K)-STOREC(I)+INC1-SEEP-DIVC
      FLOWR = FLOWR + DRAFT - DIVLAND
      STOREL(I) = FLOWR + INL + STOREL(K) - FLOWOUT
      IF(STOREL(I).GT.REQL) STOREL(I) = REQL
      FLOWOUT=STOREL(K)-STOREL(I)+INL+FLOWR
      STORET(I)=STORET(K)+INT2-FLOWS-DIVS
      IF(STORET(I).LE.0.) STORET(I)=0.
      IF(STORET(I).GE.CAPT) STORET(I)=CAPT
      FLOWS=STORET(K)-STORET(I)+INT2-DIVS
      FLOWM=FLOWS+FLOWN+INT3
      SUPPLY=DIVC+DIVS+DIVLAND+DIVN
        IF(N.EQ.1.AND.IRANK.NE.0) THEN
          SUMM(1,IRANK) = STOREC(I)
          SUMM(2,IRANK) = STORET(I)
          SUMM(3,IRANK) = FLOWR
          SUMM(4,IRANK) = FLOWN
          SUMM(5,IRANK) = FLOWS
          SUMM(6,IRANK) = FLOWM
          SUMM(7,IRANK) = STOREL(I)/22.1
          SUMM(8,IRANK) = SUPPLY
          DO 20 J=1,6
            XBIND(J,IRANK) = BIND(J,I)
20        CONTINUE
        ENDIF

C  CALCULATE ALL DEFICITS FOR THIS WEEK:
      DEFR=AMAX1(0.,  REQR-FLOWR)
      DEFM=AMAX1(0.,  REQM-FLOWM)
      DEFN=AMAX1(0.,  REQN-FLOWN)
      DEFS=AMAX1(0.,  REQS-FLOWS)
      DEFL=AMAX1(0.,  REQL-STOREL(I))
      DEF20=AMAX1(0.,REQE-STOREL(I))
      DEFSYS=DEM(II)*DSYS-SUPPLY
      IF(DEFSYS.LE.0.) DEFSYS=0.
        DEFTOT(1,I)=DEFR
        DEFTOT(2,I)=DEFN
        DEFTOT(3,I)=DENS
        DEFTOT(4,I)=DEFM
        DEFTOT(5,I)=DEFL
        DEFTOT(6,I)=DEF20
        DEFTOT(7,I)=DEFSYS

        IF(I.LT.1.AND.IRANK.EQ.0)  THEN
        WRITE(7,100) I,II
100     FORMAT(//1X,'WEEK=',I4,',',I2,9X,
     +'     RENTON',' N.F.TOLT',' S.F.TOLT',' M.S.TOLT','    L. WASH',
     +'    CED RES',' TOLT RES',' C2/DLAND',' DR-S-R-DN','    SUPPLY')
        WRITE(7,110) INC3,INT1,INT3,INL,INC1,INT2,INC2,DRAFT
110     FORMAT(1X,'INFLOWS/DRAFT          ',2F10.3,10X,6F10.3)
        WRITE(7,120) REQR,REQN,REQS,REQM,REQL,CAPC,CAPT,SEEP,
     + (DEM(II)*DSYS)
120     FORMAT(1X,'REQUIREMENTS/CAP/DEM',7F10.3,10X,2F10.3)
        WRITE(7,130) FLOWR,FLOWN,FLOWS,FLOWM,STOREL(I),STOREC(I),
```

```
     + STORET(I),RSEEP,SUPPLY
130       FORMAT(1X,'FLOW/STORE(I)/SUPPLY',7F10.3,10X,2F10.3)
          WRITE(7,140) DEFR,DEFN,DEFS,DEFM,DEFL,DIVC,DIVS,DIVLAND,
     + DIVN,DEFSYS,DEF20
140       FORMAT(1X,'DEFICITS/DIVERSIONS ',11F10.3)
          ENDIF
C   CONTINUITY CHECK FOR ENTIRE SYSTEM:
          CHECK=INC1+INC2+INC3+RSEEP-DIVC-SEEP-DIVLAND-FLOWR-STOREC(I)
     $ + STOREC(I-1)
          IF(CHECK.GT.0.001.OR.CHECK.LT.-0.001)
     + PRINT *,'CEDAR CHECK = ',CHECK,', I==',I

          CHECK=INT1+INT2+INT3-FLOWM-DIVN-DIVS-STORET(I)+STORET(I-1)
          IF(CHECK.GT.0.001.OR.CHECK.LT.-0.001)
     + PRINT *,'TOLT CHECK = ',CHECK,', I=',I
          CHECK=INL+FLOWR-FLOWOUT-STOREL(I)+STOREL(I-1)
          IF(CHECK.GT.0.001.OR.CHECK.LT.-0.001)
     + PRINT *,'LAKE WASH. CHECK = ',CHECK,', I=',I

 1001 CONTINUE

      RETURN
      END
```

Subroutine Predict

```
      SUBROUTINE PREDICT(N,I,QPRED)
      COMMON/COM5/STAT(7,2,52),MEAN(7,4,52),SDEV(7,4,52),
     + COR(7,4,52),FRAC(7,52)
      COMMON/COM6/INFLOW(7,1740)
      DIMENSION Q(3), QPRED(7,3,16)
      REAL INFLOW,MEAN

C  THIS SUBROUTINE COMPUTES THE FORECAST PERIOD SUMS VIA A
C  LAG ONE MARKOV MODEL.  STAT(X,1,IWEEK) CONTAINS THE MEANS FOR THE
C  CURRENT WEEK .  SINCE THE PREVIOUS WEEK'S
C  VALUE IS DESIRED, STAT(IWEEK-1) MUST BE USED  STAT(X,2,X) IS
C  THE STANDARD DEVIATION FOR THE CURRENT WEEK. "MEAN", "SDEV", AND
C  "COR" REFER TO THE FORECAST PERIOD STATISTICS.

      K=I-1
      KK=MOD(K,52)
      IF(KK.EQ.0) KK=52
      IF(N.EQ.1)NN=1
      IF(N.EQ.4)NN=2
      IF(N.EQ.12)NN=3
      IF(N.EQ.16)NN=4

      DO 10 J=1,7
        CM=STAT(J,1,KK)
        CS=STAT(J,2,KK)
        FM=MEAN(J,NN,KK)
        FS=SDEV(J,NN,KK)
        CORR=COR(J,NN,KK)
        IF(CORR.LT.0.20) CORR=0.0

        IF(INFLOW(J,K).LE.0) INFLOW(J,K)=0.001
        FLOW=INFLOW(J,K)*1000.
        Y=LOG(FLOW)
        Y2=FM + FS/CS*CORR*(Y-CM)
        VRF = 1.0 - CORR*CORR
        Y1 = Y2 - 1.28*FS*SQRT(VRF)
        Y3 = Y2 + 1.28*FS*SQRT(VRF)
        Q(1)=EXP(Y1)
        Q(2)=EXP(Y2)
        Q(3)=EXP(Y3)
```

```
          SUM = 0.0
          DO 30 L=1,N
            LL=MOD((K+L),52)
            IF(LL.EQ.0) LL=52
            SUM = SUM + FRAC(J,LL)
30        CONTINUE
          DO 40 M=1,3
          DO 40 L=1,N
            LL=MOD((K+L),52)
            IF(LL.EQ.0) LL=52
            QPRED(J,M,L) = FRAC(J,LL)/SUM*Q(M)/1000.
40        CONTINUE
          IF(I.EQ.262) THEN
          DO 50 II=1,N
          WRITE(2,1000) J,I,N,II,(QPRED(J,IJ,II),IJ=1,3),INFLOW(J,K+II)
1000      FORMAT(1X,4I5,4F10.3)
50        CONTINUE
          ENDIF
10      CONTINUE
        RETURN
        END
```

Subroutine Seeps

```
      SUBROUTINE SEEPS(STOREC, SEEP, RSEEP, K, I, KCITY)
      DIMENSION STOREC(1740), SMOR(1740), RETURN(1740), V1(2),
     + V2(2),  V3(2)
        DATA V1/63. 360, 19. 40/
        DATA V2/ 67. 980, 23. 300/
        DATA V3/4. 620,  3. 900/
        RETURN(1)=0.
        SMOR(1)=47. 000
        J = KCITY
        IF(STOREC(K). LT. V1(J))  THEN
          SEEP=0. 550
        ELSE
          IF(STOREC(K). LT. V2(J))  S=STOREC(K)-V1(J)
          IF(STOREC(K). GT. V2(J))  S=0. 0898*(STOREC(K)-V2(J))+V3(J)
          SEEP  =  (57. 21073779  *  S  -  106. 26536958  *  S*S
     $    + 119. 98930157  *  S**3  -  65. 70749049  *  S**4
     $    + 19. 67819518  *  S**5  -  3. 26952931  *  S**6
     $    + 0. 2840390014  *  S**7  -0. 0100367966  *  S**8
     $    - 0. 5976  )  *  13. 93  /  1000.
          IF(SEEP. LT. 0. 0)  SEEP  =  0. 0
        ENDIF
C   SEEPAGE RETURN EQUATIONS
      IF(SMOR(K). GE. 18. 0)GO TO 180
      AQ=SMOR(K)/10.
        RETURN(I)  =    46. 289826  -  769. 072418887*AQ
     $ + 3857. 3574510997  *  AQ**2  -  9005. 6000219404*AQ**3
     $ + 11272. 4394265179*AQ**4  -  7785. 7478342617*AQ**5
     $ + 2794. 5050906731*AQ**6  -  406. 40650687*AQ**7
      RETURN(I)=RETURN(I)*13. 90/100.
      GO TO 181
180   CONTINUE
      AQ=SMOR(K)/10.
        RETURN(I)  =  474. 4113  -  416. 164346028*AQ
     $ + 263. 9651929657*AQ**2  -  80. 0159082543*AQ**3
     $ + 12. 1753015378*AQ**4  -  0. 7270529578*AQ**5
      RETURN(I)=RETURN(I)*13. 93/1000.
181   CONTINUE
      IF(RETURN(I). LE. 0. 0)  RETURN(I)=0. 0
      SMOR(I)=SMOR(K)  +  SEEP  -  RETURN(I)*1. 25
      IF(SMOR(I). GE. 47. 0)  SMOR(I)=47. 0
      IF(SMOR(I). LE. 0. 0)SMOR(I)=0. 0
        KK=I-4
        IF(KK. LT. 1)KK=1
        RSEEP=RETURN(KK)
      RETURN
      END
```

Subroutine Space

```
      SUBROUTINE SPACE(XSTOREC, XSTORET, XSYS, I, II, DIVS, DIVC, CAPC, CAPT,
     + SFAC)
        DIMENSION SPRED(7,3,16)

        CALL PREDICT(4,I,SPRED)
        SC=XSTOREC
        ST=XSTORET
        DO 10 J=2,4
          SC = SC + SPRED(1,2,J)
          ST = ST + SPRED(5,2,J)
10      CONTINUE

      DIVC=(CAPT*SC-(CAPC*(ST-XSYS)))/
     $ (CAPC+CAPT)
      DIVC=DIVC + SFAC*XSYS/100.
      IF(DIVC.LE.0.0) DIVC=0.0
      DIVS=XSYS-DIVC
      IF(DIVS.LE.0) DIVS=0.0
      DIVC=XSYS-DIVS
      IF(DIVC.GE.XSTOREC.OR.DIVS.GE.XSTORET) THEN
        IF(DIVC.GE.XSTOREC) THEN
          DIVC=XSTOREC
          DIVS=XSYS-DIVC
        ELSEIF(DIVS.GE.XSTORET) THEN
          DIVS=XSTORET
          DIVC=XSYS-DIVS
        ELSE
          PRINT*, 'ERROR IN SPACE RULE'
        ENDIF
      ENDIF
      RETURN
      END
```

Subroutine Deficit

```
      SUBROUTINE DEFICIT(NWEEK,DEFTOT,BIND)
        DIMENSION DEFTOT(7,1740),NUM(9),AVE(9),TOT(9),AVEC(9),AMAXC(9),
     + AMAX(9),DEF(2),BIND(6,1740),COUNT(6)
        DATA AVE,AMAX,TOT/27*0.0/
        DATA NUM/9*0/
        CONV1=71.8
        AREA=22.1
        DO 5 K=1,6
        COUNT(K)=0.0
5       CONTINUE

C  CALCULATE FREQUENCY OF BINDING VARIABLES:
        DO 10 J=2,NWEEK
        DO 12 K=1,6
        IF(BIND(K,J).EQ.1) COUNT(K)=COUNT(K)+1
12      CONTINUE

C  CALUCLATE DEFICIT STATISTICS:
        TOTAL=0.0
        DEF(1)=0.
        DEF(2)=0.
        DO 20 I=1,7
        TOT(I)=TOT(I)+DEFTOT(I,J)
        AMAX(I)=AMAX1(DEFTOT(I,J),AMAX(I))
        IF(DEFTOT(I,J).GT.0.01) NUM(I)=NUM(I) +1
        TOTAL = TOTAL + DEFTOT(I,J)
        IF(I.EQ.7) THEN
          JJ=MOD(J,52)
          IF(JJ.EQ.0) JJ=52
          IF(DEFTOT(7,J).GT.0.01) WRITE(2,5000) J,JJ,DEFTOT(7,J)
5000      FORMAT(2X,2I4,F10.2)
        ENDIF
20      CONTINUE

        DEF(1)=TOTAL-DEFTOT(6,J)
        DEF(2)=TOTAL-DEFTOT(5,J)
        DO 15 I=8,9
        K=I-7
        AMAX(I)=AMAX1(AMAX(I),DEF(K))
        TOT(I)=TOT(I)+DEF(K)
        IF(DEF(K).GT.0.01) NUM(I)=NUM(I)+1
15      CONTINUE

10      CONTINUE

        DO 40 I=1,9
        IF(NUM(I).GT.0) AVE(I)=TOT(I)/NUM(I)
40      CONTINUE
        DO 30 I=1,4
          AMAXC(I)= AMAX(I)*CONV1
          AVEC(I)=AVE(I)*CONV1
30      CONTINUE
        AVEC(7)=AVE(7)*CONV1
        AMAXC(7)=AMAX(7)*CONV1
        AMAXC(5)=AMAX(5)/AREA
        AMAXC(6)=AMAX(6)/AREA
        AVEC(5)=AVE(5)/AREA
```

```
      AVEC(6)=AVE(6)/AREA

      WRITE(6,2000)
      WRITE(2,2000)
2000  FORMAT(/,1X,
     +'   SYSTEM          AVERAGE             MAXIMUM          CUMULATIVE',
     +'     NO.OF'/1X,
     +'   DEMAND      DEFICIT (1000 AF) DEFICIT(1000 AF) DEFICIT',
     +'(1000AF) WEEKS'/,
     +' _____________  __________________ __________________ ________',
     +'_________ ______')

      WRITE(6,2010) AVE(7),AVEC(7),AMAX(7),AMAXC(7),TOT(7),NUM(7),
     + AVE(5),AVEC(5),AMAX(5),AMAXC(5),TOT(5),NUM(5),
     + AVE(6),AVEC(6),AMAX(6),AMAXC(6),TOT(6),NUM(6)
      WRITE(2,2010) AVE(7),AVEC(7),AMAX(7),AMAXC(7),TOT(7),NUM(7),
     + AVE(5),AVEC(5),AMAX(5),AMAXC(5),TOT(5),NUM(5),
     + AVE(6),AVEC(6),AMAX(6),AMAXC(6),TOT(6),NUM(6)

2010  FORMAT(1X,
     +'M & I SUPPLY ',F7.2,' (',F4.0,' CFS)',F7.2,' (',F4.0,' CFS)',
     +2X,F7.2,9X,I4/1X,
     +'LW RULE CURVE',F7.2,' (',F5.1,' FT)',F7.2,' (',F5.1,' FT)',
     +2X,F7.2,9X,I4/1X,
     +'LW 20 FT ELEV',F7.2,' (',F5.1,' FT)',F7.2,' (',F5.1,' FT)',
     +2X,F7.2,9X,I4)

      WRITE(6,2020) (AVE(I),AVEC(I),AMAX(I),AMAXC(I),TOT(I),
     +NUM(I),I=1,4)
      WRITE(2,2020) (AVE(I),AVEC(I),AMAX(I),AMAXC(I),TOT(I),
     +NUM(I),I=1,4)

2020  FORMAT(1X,
     +'RENTON REQ.   ',F7.2,' (',F4.0,' CFS)',F7.2,' (',F4.0,' CFS)',
     +2X,F7.2,9X,I4,/1X,
     +'N.F.TOLT REQ. ',F7.2,' (',F4.0,' CFS)',F7.2,' (',F4.0,' CFS)',
     +2X,F7.2,9X,I4/1X,
     +'S.F.TOLT REQ. ',F7.2,' (',F4.0,' CFS)',F7.2,' (',F4.0,' CFS)',
     +2X,F7.2,9X,I4/1X,
     +'MAIN TOLT REQ',F7.2,' (',F4.0,' CFS)',F7.2,' (',F4.0,' CFS)',
     +2X,F7.2,9X,I4)

      WRITE(6,2030) (AVE(I),AMAX(I),TOT(I),NUM(I),I=8,9)
      WRITE(2,2030) (AVE(I),AMAX(I),TOT(I),NUM(I),I=8,9)
2030  FORMAT(/,1X,'TOTAL (LWRC) ',4X,F9.2,9X,F9.2,5X,F9.2,9X,I4/,
     +1X,'TOTAL (LW20'')'4X,F9.2,9X,F9.2,5X,F9.2,9X,I4)
      PRINT *, (COUNT(K),K=1,6)
     RETURN
     END
```