University of Washington
Department of Civil and Environmental Engineering

WATER RESOURCE SYSTEM RELIABILITY UNDER DROUGHT CONDITIONS: THE SEATTLE WATER SUPPLY SYSTEM AS A CASE STUDY

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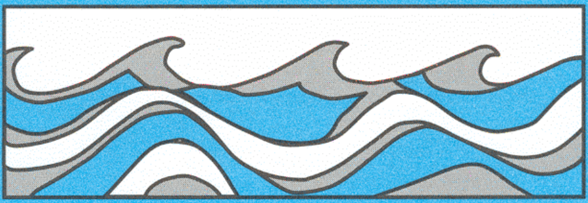

Water Resources Series
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by

Sarah H. Draper, Richard N. Palmer, Dennis P. Lettenmaier,
and Stephen J. Burges

Technical Report No. 72

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Principal Investigators:	Stephen J. Burges, Professor of Civil Engineering, University of Washington Dennis P. Lettenmaier, Research Associate Professor of Civil Engineering, University of Washington
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Abstract

This report investigates several potential means of increasing the resistance of water supply systems to drought conditions through improved management and planning, focusing upon the Cedar and Tolt River systems of Western Washington. Initially, the ability of drought indices to define and forecast hydrologic drought is examined. Particular emphasis is placed on the applicability of the widely used Palmer Drought Index to act as a precursor of hydrologic drought in Western Washington. In general, this index provides less accurate forecasts of future runoff deficiencies than do hydrologic forecasting methods currently in use.

A more useful drought management tool appears to be simulation modeling. A detailed simulation model of the Seattle Water Department's Cedar/Tolt system is developed that incorporates a method of characterizing system reliability in terms of supply deficits. The model study indicates that system expansion proposed by the Seattle Water Department is necessary if the system is to supply projected year 2000 demands reliably. System reliability would be markedly improved by implementation of the "City Light Plan" to increase the volume of active storage in the Cedar River reservoir. The model study also indicates that a reduction in seepage loss from the Cedar reservoir may significantly improve system reliability, contrary to the results of earlier analyses. The effects of alternate operating policies on system reliability and the role of instream flow requirements and Lake Washington management are also discussed. The model study illustrates the advantages of a demand-deficit approach as compared with conventional safe yield analysis.

Acknowledgements

The research reported herein was supported by a matching grant from the Office of Water Research and Technology, U.S. Department of the Interior, administered by the State of Washington Water Research Center. Non-federal matching support as in-kind services and research funds was provided by the Seattle Water Department. The assistance of employees of the Department, particularly Mr. Tom Johanson, in providing hydrometeorological data files, and Mr. William Mancinelli, who assisted us in codifying the physical configuration and operating constraints of the demonstration system, is gratefully acknowledged. Dr. Robert T. Milhous, of the State of Washington Department of Ecology (now with the Instream Flow Group, U.S. Fish & Wildlife Service, Fort Collins, Colorado) provided helpful assistance in the early stages of the project.

The work described in this report in large part constitutes the Master's Thesis of the first author. K.M. Leytham and D.C. Garen, both graduate students in the Department of Civil Engineering, University of Washington, also participated in earlier stages of the project.

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CHAPTER I

INTRODUCTION

Purpose of the Study

Western Washington is a region that has traditionally had an abundant supply of water. Recent increases in the area's population have begun to tax existing water supply facilities more heavily, however. In addition, in recent years the region has experienced several relatively severe droughts which have emphasized the fragility of the buffering provided by existing water supply systems. The drought of 1976-77 in particular made evident a need, not only for improvements to existing physical systems, but for improved facilities operation and drought management strategies. This study explores several potential means of increasing the resistance of water supply systems to drought conditions through improved management and planning. This research focuses upon the Cedar and Tolt River System, which supplies the municipal and industrial water needs of the City of Seattle.

The effectiveness of drought management policies depends largely upon the operators' ability to define and predict droughts accurately. A number of indices have been developed for use in defining periods of drought and several of these are reviewed here with reference to their utility in a water supply application. The National Weather Service uses an index developed by Palmer (1965). This index was developed for use in climates rather different from that of Western Washington, but has been applied to this region nevertheless. The Palmer index has not, to the authors' knowledge, been previously tested as a quantitative index of hydrologic drought. Such an index would be particularly useful if it could function as a predictor of streamflow volumes.

In the Cedar/Tolt system, effective management strategies cannot be devised without a better understanding of system interactions. The present physical system includes two reservoirs, a large lake, and an underground aquifer fed by seepage from one of the reservoirs. The operation of the system as a water supply facility is constrained by instream flow requirements. It would be quite difficult to understand the interaction of factors such as these within the system without the help of a conceptual model. The Seattle Water Department plans to expand the physical system to meet growing demands; modeling is also needed to show how much the proposed modifications will affect system performance, so that expansion may be efficiently planned.

A digital simulation model is useful in an application such as this because it can indicate what supply deficits are to be expected when a system receives a specified set of inflows and demands and is operated in a specified manner. This information can be used to estimate how and when the system should be expanded, and how it should be operated to keep deficits below an acceptable level. Traditionally, system reliability has been characterized in terms of the yield that can be expected from the system under specified critical conditions. However, an analysis that emphasizes expected deficits at varying demands may supply some useful information not given by a yield analysis. The Cedar/Tolt system model can serve a dual function, providing an opportunity to experiment with this concept of demand-deficit analysis.

This study addresses the issue of drought in the context of the Seattle Water supply sysem in two ways. First, drought indices, which may serve as precursors of droughts, are reviewed in Chapter II, and one widely used index, the Palmer Index, is compared to more traditional hydrologic forecast methods. Second, a detailed simulation model of the Cedar/Tolt system is developed. This model can be used either to assess the severity, as reflected in water supply shortfalls, of a particular drought condition (i.e., sequence of abnormally low streamflows) or to estimate the non-failure yield of the system for a particular critical drought sequence. A physical description of the Cedar/Tolt system, and history of the water supply development of this system, is given in Chapter III. The simulation model is described in Chapter IV, and selected results and conclusions are included in Chapter V.

CHAPTER II

DROUGHT INDICES: AN OVERVIEW

The Problem of Drought Description

Although there is general agreement that drought is an important phenomenon, there is little agreement about the exact meaning of the term. Drought refers to dry weather or a shortage of water, and has been given a variety of more specific meanings, including the following physical definitions:

1. "... a spell of dry weather" (Steila, 1972).
2. "... a prolonged and abnormal moisture deficiency" (Palmer, 1965).
3. "... lack of rainfall so great and long continued as to affect injuriously the plant and animal life of a place and to deplete water supplies both for domestic purposes and for the operation of power plants, especially in those regions where rainfall is normally sufficient for such purposes," (Chow, 1964).
4. "... a period of deficient rainfall that is seriously injurious to vegetation," (Steila, 1972).
5. "A drought condition is created if, in the economic development of a region, man creates a demand for more water than is normally available," (Steila, 1972).
6. "... an 'absolute' drought ... a period of 14 consecutive days without a hundredth of an inch on any one day," (Steila, 1972).
7. "... a period of 21 days or more with rainfall 30 percent or more below normal," (Steila, 1972).
8. "... 15 days with no rain," (Steila, 1972).
9. "... a rainless period during which the temperature at 1 p.m. is still increasing (after a considerable rise), the relative humidity at 1 p.m. is 40% or less (after a considerable fall) and is still falling, the absolute humidity varies within narrow limits, and clouds are few," (Steila, 1972).
10. "Drought is a phenomenon taking many forms, but its most specific and most essential feature is a disparity between the plant's requirements of moisture and the latter's supply from the soil," (Steila, 1972).

These definitions hold little meaning in the context of water resources management, where storage provides a buffer against seasons or years when runoff is insufficient to meet demands. For such a context, Linsely, et al. (1975) suggest the following definition:

> "Hydrologic drought may be defined as a period during which streamflows are inadequate to supply established uses under a given water-management system," (Linsely, et al., 1975).

Similarly, Russell, et al. (1970) define drought as

> "The potential shortage of water engendered by interaction between a climatic event and the adequacy of the safe yield of a system in relation to the level of demand."

It is clear that the range of different definitions results from different requirements for moisture. In some respects, one could consider water shortages resulting from overdevelopment of an area to cause a "permanent" drought, however, such situations will not be considered here; shortages of moisture are assumed to be relative to normally occurring or expected conditions. The problem of inconsistent definitions is alleviated by dividing drought phenomena into types reflecting specific fields of interest; thus, one hears of agricultural, hydrologic, meteorologic, or atmospheric drought. There is no reason to assume, however, that these terms are defined in a consistent manner. The time span that a dry spell or water shortage must encompass before it can be called a drought will vary depending on the specific field of interest.

Before the nature and occurrence of drought periods in a certain location can be studied, a basis for delimiting such periods must be established. This basis of definition should be relevant to the aspect or effect of drought that is of interest (such as climate, crop growth, streamflow, or fire hazard). A drought period is characterized by its severity as well as its duration; if simple moisture deficits relative to the mean are being analyzed, for instance, severity is indicated by deficit volume. A more complex definition of drought requires a more thoughtful characterization of severity. One approach to delimiting and describing drought periods is the use of a drought index. An index is a single number which indicates the severity of drought conditions as related to one type of drought (or one effect of moisture deficiency). A number of indices have been developed; some of which are described in this chapter.

Types of Drought

One type of drought for which indices have been developed is agricultural drought, which is defined by the effect that drier-than-normal weather has on plants. Soil moisture is the crucial factor here, and detailed information about the crops being grown in the area may be required. Of greater interest here is hydrologic drought, which involves below-normal streamflows. Soil moisture is important here as well, because it affects how much precipitation is transformed into streamflow. Indices have also been developed for meteorological drought, which is characterized by a shortage of precipitation relative to the amount that an area normally receives. In some cases, meteorological drought indices, such as the Palmer Index (Palmer, 1965) which is tabulated by the National Weather Service, can serve as surrogates for hydrologic drought.

These drought classifications and definitions are by no means absolute. For instance, the Palmer Index is referred to as an index of meteorological drought, although the method involves a soil moisture balance. The moisture balance is used to determine what amount of precipitation would result in a return to seasonally normal conditions at a certain time, but the drought is still explicitly defined in terms of precipitation. Palmer (1965) suggests that a lack of precipitation may have direct economic effects. This assumes that economic activity is established at a level corresponding to the availability of water; an assumption which may or may not be accurate for any specific region.

Agricultural Drought Indices

An example of an explicitly agricultural drought analysis is van Bavel's (1953) method, which attempts to relate soil moisture conditions to plant growth. The method involves basing a soil moisture balance on precipitation records and estimates of evapotranspiration. A drought-day is described as a 24-hour period "in which the soil moisture stress (moisture tension plus osmotic pressure) exceeds a limit, which, on the basis of experimental evidence, may be taken as a point at which the productive processes of a crop are being appreciably decreased". The number of drought-days is computed using the season length and the limiting soil moisture tension and rooting depth of the particular crop under study. The critical number of drought-days for that crop can be estimated based on past growing seasons; and the risks that a farmer faces in any particular water shortage situation thus estimated. In an irrigated system, the buffering effects of irrigation facilities must be taken into account.

Steila (1972) briefly describes an index developed by Keetch and Byram of the U.S. Forest Serivce to indicate the danger of vegetation fires. A soil moisture balance is carried out using precipitation and actual evapotranspiration, assuming an 8-inch soil moisture storage capacity. The rate of soil moisture depletion is modeled based upon the density of vegetation cover in the area, which is related to mean annual rainfall. A drought factor that the area, which is related to mean annual rainfall. A drought factor that indicates the degree of drying and relates to the flammability of organic fuels is compared to the volume of available moisture to give an indication of fire danger.

Hydrologic drought indices are similar to agricultural indices in that soil moisture is emphasized. However, the hydrologic interest in soil moisture relates to expected runoff response to subsequent rainfall, which is reduced as soil moisture is depleted. One such index is the Antecedent Precipitation Index, or API (McQuigg, 1954). Calculation of the API is based on the assumption that soil moisture decreases logarithmically with time between rainstorms. If I_0 represents the initial API value, I_t the index t days later, and k a recession factor, then

$$I_t = I_0 k^t.$$

During a storm the API, which has units of depth (inches), is increased by an amount equal to the depth of precipitation that falls. As Linsley, et al. (1975) point out, the use of precipitation minus runoff would give a more accurate value, as would taking into account the effects of temperature and wind. This however, would detract from the extreme simplicity of the index.

Precipitation Deficit Methods

Another approach to drought analysis is to define drought periods as deficit periods within a precipitation or streamflow record, without estimating soil moisture or performing a water balance. In some cases, a definition of meteorological drought based on precipitation data alone may be useful.

and end of drought periods in a historic rainfall record, as well as their severity. In this method, monthly means of rainfall are calculated and subtracted from actual rainfall to give deficits or excesses. The effect of antecedent conditions in a particular month is approximated by multiplying the rainfall deficit or excess of the previous month by a weighting factor and adding this value to the present month's rainfall to obtain an effective rainfall quantity. A mean monthly deficit is then calculated for each of the 12 months, using the differences between effective rainfall and mean monthly rainfall. The mean annual deficit is then found. These various values are then used, with a set of rules and tests, to define the beginning and end of drought periods. A drought index can also be calculated with the equation:

$$YD = \frac{\sum_{1}^{D} \text{excess deficits}}{\sum_{1}^{D} \text{mean monthly deficits}} * D$$

where D is the length of the drought in months. This index is meant to enable the intensities of droughts occurring in different seasons to be compared.

<u>Water Balance Methods</u>

The water balance concept provides the basis for several drought index methods, including the widely used Palmer (1965) Index. As with most of the other indices, soil moisture is the critical concern. The water balance concept is described by Thornthwaite and Mather (1955), and is commonly attributed to Thornthwaite. A central concept is potential evapotranspiration (PE), which is defined as the amount of water which will be lost from a surface completely covered with vegetation if the vegetation is not limited by soil moisture. Thornthwaite felt that satisfactory estimates of PE could be obtained using location and temperature alone.

Thornthwaite also developed a water balance accounting method in which PE is compared to precipitation to determine periods of moisture excess or deficiency. Monthly average values of P-PE are summed to obtain an accumulated potential water loss. This is used to estimate the change in soil moisture storage during the month. Other quantities computed include actual evapotranspiration, moisture deficit or surplus, runoff, snowmelt and total moisture retention.

Steila (1972) created a drought index with the Thornthwaite water balance as its basis. The moisture accounting was carried out using monthly precipitation and temperature records, with the index computed as the difference between estimated soil moisture and the long term soil moisture mean for that month.

The Palmer Index

Palmer (1965) developed a drought index (PDI) which is widely used in the U.S. by the National Weather Service. The PDI was developed and tested using data from a number of locations in the eastern and central states. It has been applied in many western states as well, including Washington. The extensive use of this index, which is based on the water balance concept, merits its consideration separately. In the following section, the extent to which the PDI can be used as a precursor of hydrologic drought is assessed..

Palmer modified the water balance concept in developing the PDI. Palmer's method attempts to combine representations of hydrologic-related factors (soil moisture) and vegetation-related factors (PE) with meteorological factors (precipitation) to give an index that is designed to reflect both the hydrologic and agricultural effects of drought. The index is explicitly defined in terms of precipitation quantities, however, and is therefore referred to (perhaps incorrectly) as meteorological.

Palmer's method stems from Thornthwaite's, and incorporates the concepts of PE and the water balance. The algorithm carries out a moisture balance accounting involving precipitation, evaporation, soil storage, and runoff, using historic records of precipitation and temperature. The long-term means of each of the elements in the balance are used to derive seasonal coefficients for the location under study. These coefficients are then used as a baseline against which to determine periods of abnormal moisture deficiency or excess within the precipitation record. Palmer has derived standards for defining the beginning and end of drought periods as well as correction factors to balance regional differences in index values.

The PDI was developed using monthly average values of precipitation and temperature to compute monthly index values. The National Weather Service has also computed weekly values, but the monthly time increment is the norm. One justification for this is that the potential evapotranspiration computation has been estimated to be in error by 100 percent or more on individual days, but only by 10 to 15 percent for periods of two weeks or longer.

Soil storage of water is handled by dividing the soil into an upper layer containing an assumed one-inch of water at field capacity, and a lower layer with a capacity depending on the soil characteristics of the site being considered. Moisture cannot be removed from the lower layer until all of the available moisture has been removed from the upper layer, and the lower layer cannot be recharged until the upper layer has been recharged. Evapotranspiration loss from the upper layer is assumed to take place at the potential rate. It is assumed that loss from the lower layer depends on initial moisture content, PE, and the total available water capacity (AWC) of the soil.

The PDI computation yields a drought severity index that takes into account wet or dry spell duration as well as severity. Extreme droughts are associated with index values of about -4. The ordinate scale is commonly broken into one unit intervals. The index levels are labeled severe (-3), moderate (-2), mild (-1), and normal (0). Wet spells of classes 1 through 4 are referred to in the same terms. Since the index reflects cumulative precipitation, it is possible to determine the amount of precipitation required to raise or lower the index to a specified threshold. It is also possible, using criteria developed by Palmer (1965) to determine whether the index is likely to remain above or below a threshold in the subsequent period (month). Although Palmer refers to this as the probability that a drought has been established or has ended,the terminology is not consistent with that used in probability theory.

Streamflow Forecasting Potential of the Palmer Drought Index

Although the PDI has some apparent theoretical advantages for identifying meteorological and agricultural droughts, and is widely used to assess the severity of these kinds of droughts, its applicability to identification and forecasting of streamflow deficiencies is less clear. The Seattle water supply system, which draws water from two Western Washington streams, provides an interesting case study. The system, described in detail in Chapter III, has relatively small storage relative to mean runoff. Therefore, the ability to forecast runoff deficiencies several months in advance, allowing early implementation of protective measure, such as water conservation, is an important element in efficient operation of the system. Lettenmaier and Waddle (1978) and Lettenmaier, et al. (1980) have reviewed forecasting methods for this system. If the PDI is to have operational utility from a water resources standpoint, it must perform better than the existing alternatives.

Palmer (1965) briefly examined the utility of the PDI in forecasting future precipitation by attempting to relate monthly precipitation volumes to the previous month's PDI. He concluded that the PDI may be useful for predicting precipitation in continental climates and suggested that a good deal of this precipitation may represent moisture re-evaporated from land areas. The validity of his analysis will not be discussed here, however. Palmer's conclusions clearly do not apply to the coastal mountain climate of Western Washington, where precipitation volumes depend on the movement and moisture content of air masses from the Pacific Ocean. One would not expect the PDI to function as a predictor of precipitation in this region.

It is more likely that the PDI can serve to forecast future streamflow, since it takes into account precipitation, evapotranspiration, and soil moisture conditions, all of which are determinants of runoff. As an initial step in this investigation, a graphical analysis was made to compare the general behavior of PDI values representing different regions of Western Washington, and to determine whether the index values corresponded well to either present or future streamflow.

The PDI is computed by the National Weather Service for three regions in Western Washington: Puget Sound Lowlands; East Olympic/Cascade Foothills; and Cascade Mountains West (Magnuson, 1968). PDI records for the period 1953-76 were plotted coincidentally with records of estimated inflows to the Cedar River (URS, 1981), which supplies approximately 70 percent of the municipal and industrial water supply for the City of Seattle.

Inflows to the Cedar River from three subdrainages were included, and are classified as Cedar Inflows I, II, and III. These correspond roughly to the headwaters drainage, heavily affected by snowmelt; an intermediate drainage affected both by snowmelt and rainfall, and a low elevation drainage dominated by rainfall.

A representative plot of Cedar Inflow I and the Cascade Mountain West PDI for the period January 1953-October 1958 is shown in Figure 1 (note that streamflow is plotted as the residual from the monthly mean). Similar comparisons of runoff records and the PDI values for the three regions allowed the following conclusions:

1.) The three inflow records differ markedly in the magnitude and timing of their peaks and troughs, whereas the three indices tend to parallel one another. There is no clear correlation between any one flow record and one index, but there is a rough correspondence of mountain index to mountain inflow and lowland index to lowland inflow.

2.) The mountain and lowland indices usually parallel one another, but this pattern may be broken for periods of several months.

3.) The index records have more prolonged excursions from the mean and vary much less in the short term than do the streamflow records. This is to be expected, since the index is designed to filter out brief interruptions of prolonged spells.

4.) The indices tend to follow the same positive and negative trends as the streamflow residuals, but there is no apparent tendency for the trend of the indices to precede the trend of the streamflows.

To further analyze the PDI's forecasting potential, correlations between the PDI and streamflow were compared to the autocorrelations of three streamflow records. The PDI record used here was for the Cascade Mountains West. The Cedar River inflow records were not used in this analysis because they are derived rather than gaged flows, instead gaged flow records from three rivers in the same region of Western Washington were used:

Station 1: Skykomish River near Goldbar, Station 12-1345, U.S. Geological Survey (USGS), rated good

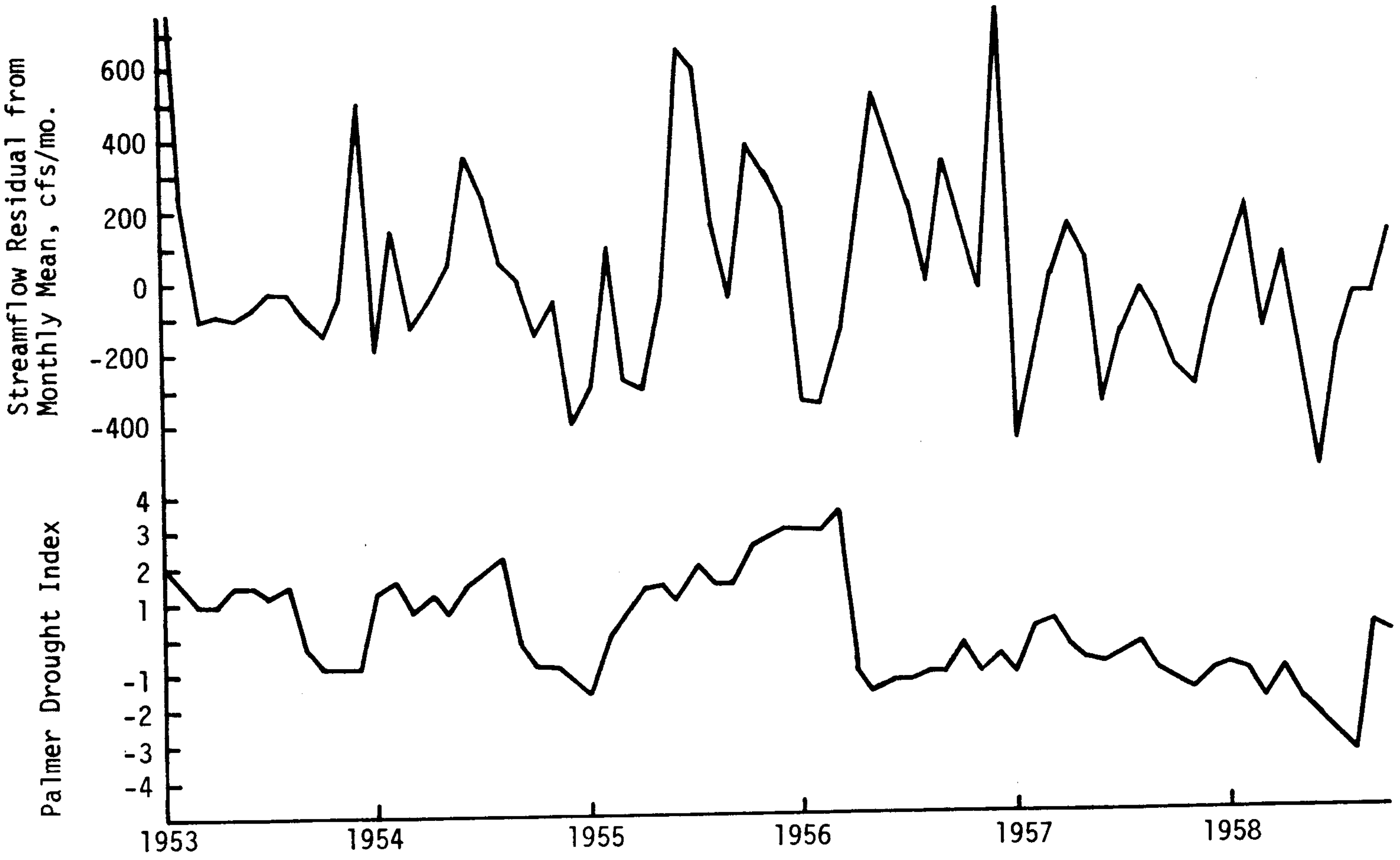


Figure 1. Variation in Palmer Drought Index and Cedar River Inflow 1, January 1953-October 1958.

Station 2: South Fork Stillaguamish River near Granite Falls, Station 12-1610, (USGS excellent)

Station 3: Sauk River near Sauk, Station 12-1895, (USGS good)

All of these drainages are affected by a mixture of smowmelt and rainfall, as is true for most Cascade Mountain drainages. The correlation coefficients were computed for each month to reflect seasonal variations as follows:

$$\hat{\rho}_{mj} = \frac{\sum_{i=1}^{N} [P_{im} - MP_m)(F_{i,m+j} - MF_{m+j})]}{(SP_m)(SF_{m+j})(N)}$$

where $\hat{\rho}_{mj}$ = monthly correlation estimate for month m at a lag of j months.

i = year

N = total number of years

P = predictor, either flow or PDI

MP = mean predictor

F = flow

MF = mean flow

SP = standard deviation of predictor

SF = standard deviation of flow

In addition to the seasonal correlations, gross correlations at lags 0 through 6 were computed using the entire data records, normalized by subtracting monthly means and dividing by monthly standard deviations.

Selected results of these correlation tests are presented in Figures 2-15 and Tables 2-5. The results vary somewhat between the three streamflow records but usually show the same general trends. In terms of gross correlation (Table 1), the PDI and same-season (lag 0) streamflow have a $\hat{\rho}$ of approximately 0.45; this indicates about how well PDI-defined droughts correspond to streamflow-defined droughts within the record as a whole. At greater lags,

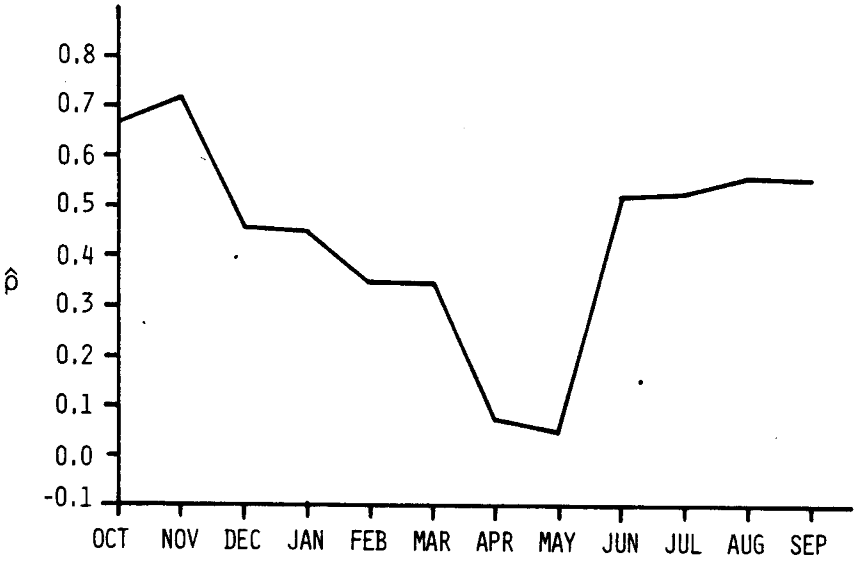


Figure 2. Lag Zero Correlation Between PDI and Streamflow: Station 1 (U.S.G.S. Station 12-1345

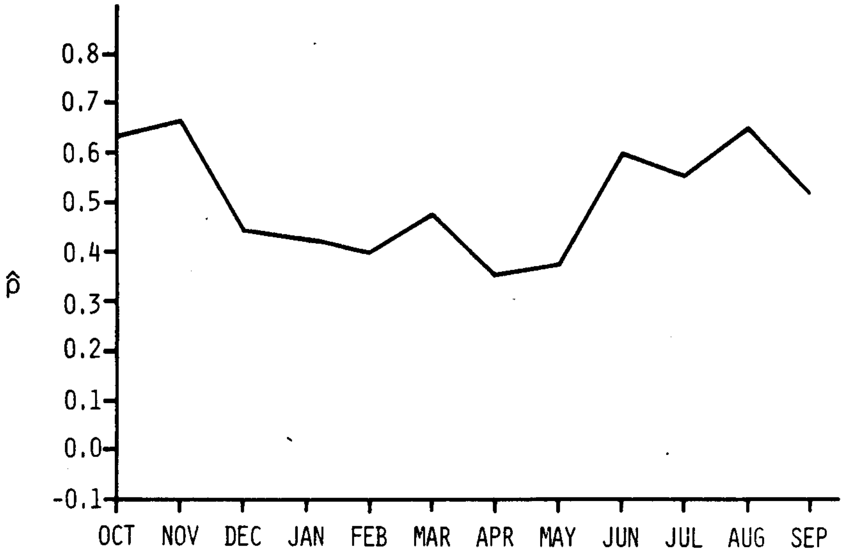


Figure 3. Lag Zero Correlation Between PDI and Streamflow: Station 2 (U.S.G.S. Station 12-1610

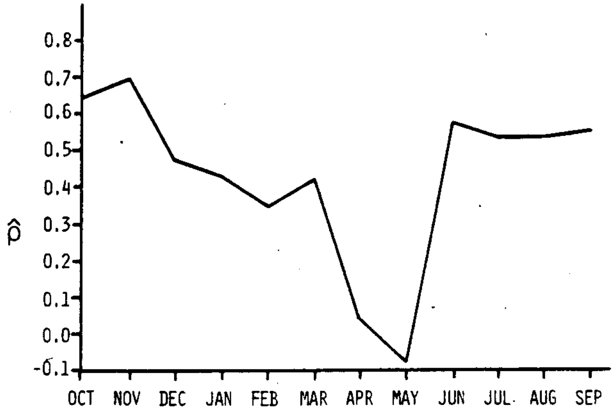


Figure 4. Lag Zero Correlation of PDI with Streamflow: Sta. 3 (U.S.G.S. 12189500)

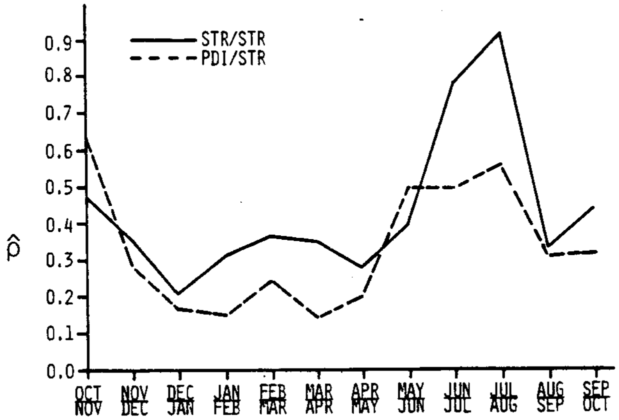


Figure 5. Lag One Correlations of PDI and streamflow (STR) with streamflow: Station 1

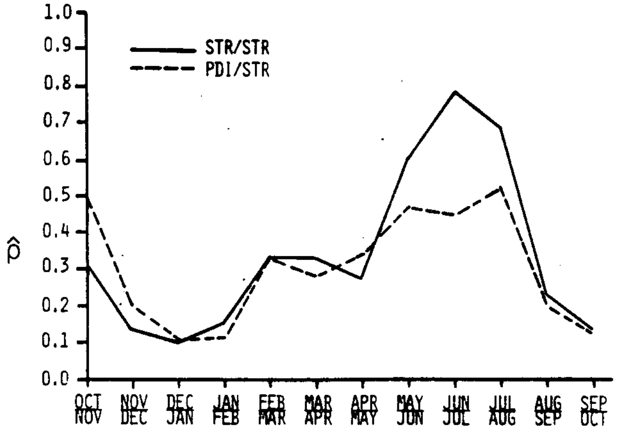


Figure 6. Lag One Correlations of PDI and streamflow (STR) with streamflow: Sta. 2

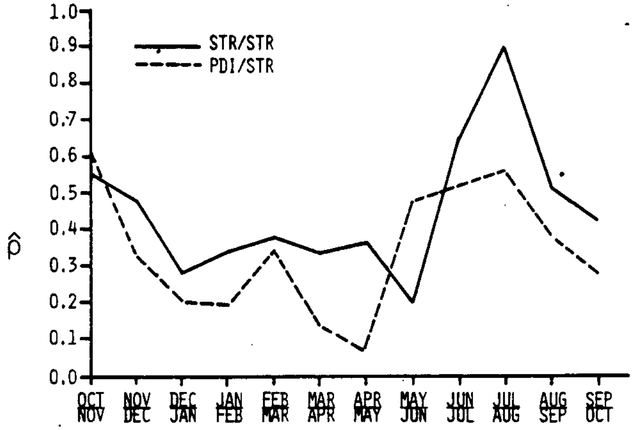


Figure 7. Lag one correlations of PDI and streamflow (STR) with streamflow: Sta. 3

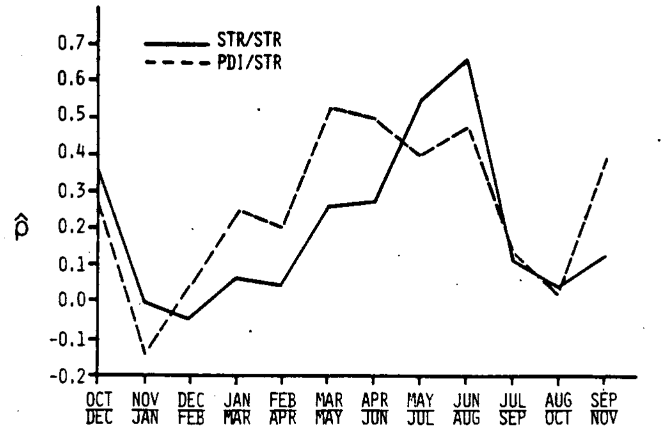


Figure 8. Lag two correlations of PDI and streamflow (STR) with streamflow: Sta. 2

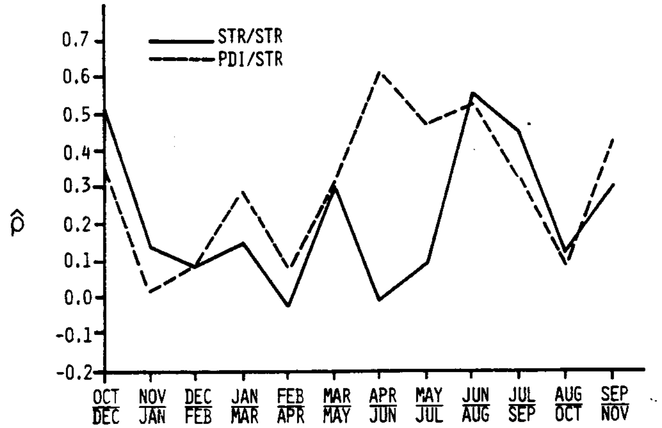


Figure 9. Lag two correlations of PDI and streamflow (STR) with streamflow: Sta. 3

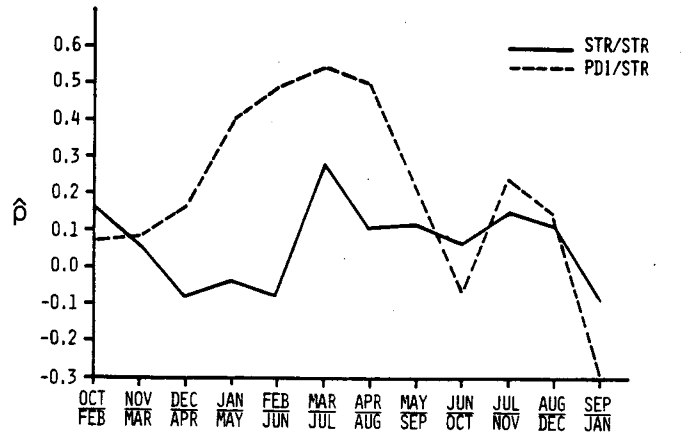


Figure 10. Lag four correlations of PDI and streamflow (STR) with streamflow: Sta. 2

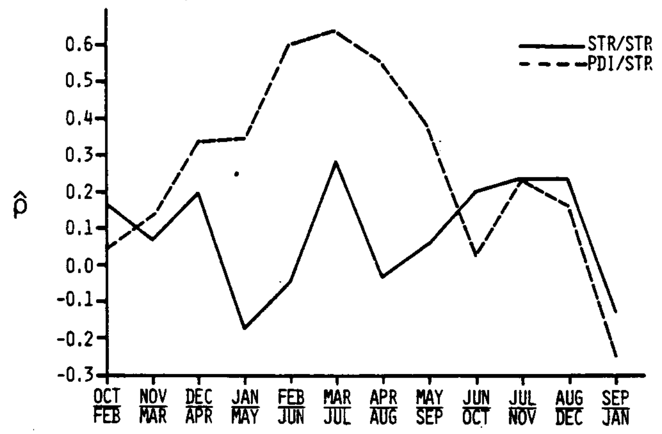


Figure 11. Lag four correlations of PDI and streamflow (STR) with streamflow: Sta. 3

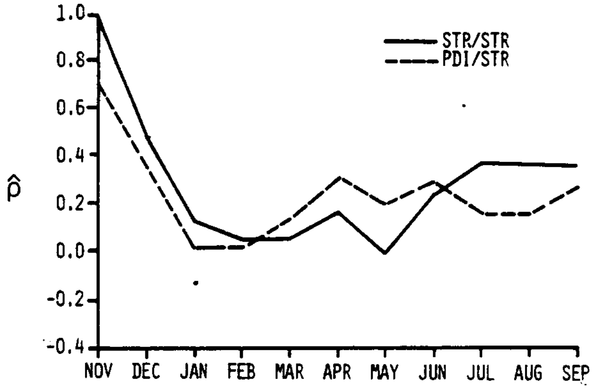


Figure 12. Correlation of NOVEMBER PDI and Streamflow (STR) with streamflows in later months

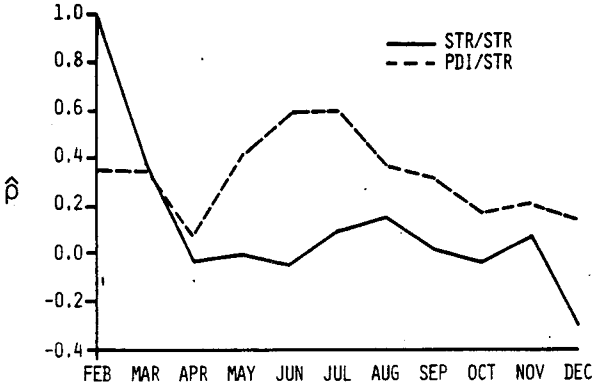


Figure 13. Correlation of FEBRUARY PDI and Streamflow (STR) with streamflows in later months

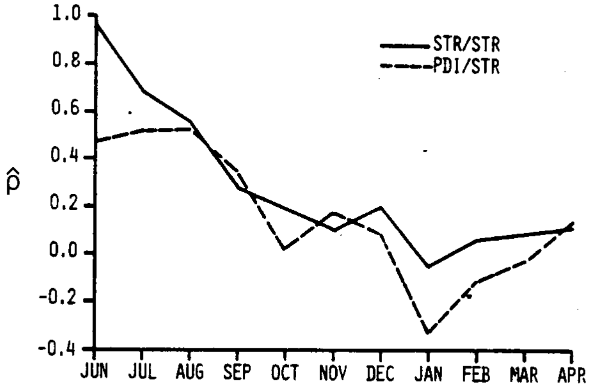


Figure 14. Correlation of JUNE PDI and Streamflow (STR) with streamflows in later months

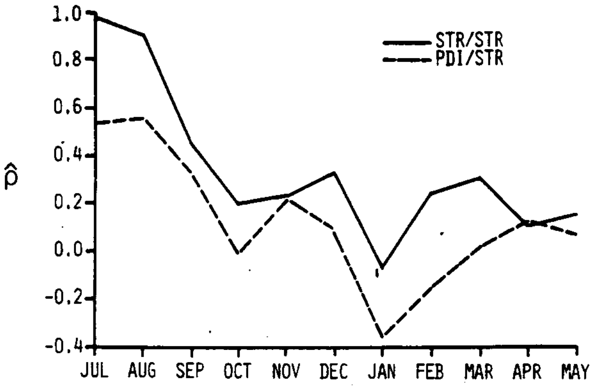


Figure 15. Correlation of JULY PDI and Streamflow (STR) with streamflows in later months

Table 1. Gross Correlations Within Streamflow Data (STR) and Between PDI and Streamflow Data.

		Lag (months)						
Sta.	Predictor	0	1	2	3	4	5	6
1*	STR	1.0	.44	.21	.09	.06	.06	.06
	PDI	.45	.35	.28	.22	.19	.15	.13
2	STR	1.0	.35	.21	.08	.08	.04	.06
	PDI	.52	.40	.33	.27	.24	.19	.18
3	STR	1.0	.47	.23	.13	.10	.08	.07
	PDI	.43	.34	.27	.22	.19	.16	.13

* Station numbers are abbreviated in all tables.

Station 1 = USGS 12-1345
Station 2 = USGS 12-1610
Station 3 = USGS 12-1895

Table 2. Correlation of Monthly Flow (STR) and PDI With Flow Occurring in the Following June

		Month of Predictor							
Sta.	Predictor	Oct.	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May
1*	STR	.019	.265	-.206	.038	-.062	.155	-.002	.387
	PDI	.162	.260	.264	.409	.595	.633	.599	.493
2	STR	.097	.258	-.054	-.041	-.081	.211	.276	.601
	PDI	.085	.134	.192	.313	.489	.540	.494	.411
3	STR	-.011	.241	-.102	.059	-.041	.262	-.014	.196
	PDI	.238	.296	.289	.403	.588	.618	.611	.475

*See Table 1

Table 3. Correlation of Monthly Flow (STR) and PDI with Flow Occurring in the Following July

		Month of Predictor							
Sta.	Predictor	Nov.	Dec.	Jan.	Feb.	Mar.	Apr.	May	June
1	STR	.299	-.086	.162	.041	.179	-.024	.300	.785
	PDI	.129	.253	.402	.550	.613	.514	.443	.488
2	STR	.358	-.078	.109	.055	.379	.219	.554	.782
	PDI	.089	.182	.307	.463	.546	.466	.397	.453
3	STR	.368	.029	.199	.096	.280	.011	.095	.645
	PDI	.158	.310	.452	.596	.646	.554	.473	.521

Table 4. Correlation of Monthly Flow (STR) and PDI With Flow Occurring in the Following August

		Month of Predictor							
Sta.	Predictor	Dec.	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.
1	STR	.029	.162	.062	.111	-.123	.191	.722	.915
	PDI	.245	.381	.520	.548	.532	.493	.509	.559
2	STR	.128	.107	.049	.057	.109	.422	.664	.682
	PDI	.242	.330	.442	.426	.499	.473	.481	.522
3	STR	.131	.268	.155	.300	-.036	.082	.562	.905
	PDI	.299	.440	.565	.605	.563	.516	.529	.562

Table 5. Correlation of Monthly Flow (STR) and PDI With Flow Occurring in the Following September

		Month of Predictor							
Sta.	Predictor	Jan.	Feb.	Mar.	Apr.	May	Jun.	Jul.	Aug.
1	STR	.154	.038	.133	.068	.065	.268	.320	.331
	PDI	.230	.197	.196	.215	.298	.273	.244	.307
2	STR	.214	-.057	.068	.114	.118	.104	.117	.234
	PDI	.265	.125	.128	.135	.228	.179	.139	.210
3	STR	.221	.014	.162	-.020	.058	.290	.458	.520
	PDI	.373	.326	.328	.316	.377	.353	.328	.387

the PDI is a slightly better predictor than streamflow, but neither is good. In a hydrologic system like the Western Cascades streamflow variations are strongly seasonal in nature, and seasonal correlations ought to vary significantly and be much more informative than gross correlations. The rest of this discussion will concern seasonal correlations.

The seasonal lag zero correlations are plotted in Figures 2-4, which show how well the PDI corresponds to streamflow volumes occurring in the same month; there is a marked seasonal variation. The PDI indicates flow volumes quite well ($\hat{\rho} > 0.5$) in the summer and fall, but less well in the winter and spring, and poorly in April and May. The reason for this is simple: the PDI does not take into account the accumulation and ablation of the snowpack. In the months of June through November streamflows are affected mostly by rainfall and soil moisture. In the winter, the relationship between precipitation and runoff is highly dependent upon temperature; freezing precipitation contributes to snowpack rather than streamflow. In the spring, streamflow consists mainly of snowmelt runoff and therefore does not correspond in volume to current precipitation or current PDI.

Examination of the seasonal lag 1 correlation in Figures 5-7 indicates that streamflow is a better short term predictor than the PDI, especially during the critical summer months, which have values of ρ as high as 0.9. At a lag of two months, as shown in Figures 8 and 9, the pattern of seasonal correlations varies noticeably between the three streamflow records. Neither predictor has a clear advantage; and neither appears very useful except during the summer. At longer lags, particularly lag 4 as shown in Figures 10 and 11, streamflow is consistently a poor predictor and the PDI has a clear advantage. Winter and early spring PDI's correlate reasonably well ($\hat{\rho} = 0.4$ to 0.7) with summer streamflows. It appears that the winter PDI gives some indication of relative snowpack accumulation, thereby indicating the relative size of the following summer's flows.

In Tables 2-5 the correlation results are rearranged to show which predictors are most useful in the case of summer flows. Summer streamflows have higher autocorrelations only at lags of one or two months. Spring PDI's, on the other hand, correlate with summer streamflows at ρ values of about 0.4 to 0.6. Although September is a critical month in the Cedar/Tolt system, with both low flows and low reservoir storage levels, neither predictor is useful for estimating September flows at any number of months' lag. In Figures 12-15 correlations are plotted as correlograms. The predictor in each month is correlated with streamflows occurring various numbers of months in the future. These correlograms are plotted for selected months to illustrate the variation and range of the results.

These results seem to indicate that the PDI is a better long-term predictor than streamflow. The PDI apparently functions as an indirect gauge of relative snowpack accumulation. The next question to ask is whether the PDI has any advantage over more direct methods of measuring or modeling snowpack accumulation and ablation. Lettenmaier and Waddle (1978) have applied a modified version of Tangborn's (1977) snowmelt model to the Cedar River. This model is designed to forecast the total volume of streamflow that can be expected during a time period of specified length (such as 90 or 120 days) following the date of prediction. The flow forecast for a single month can be found by subtraction. A series of these monthly flow predictions can be compared to the series of actual flow volumes, and the accuracy of prediction expressed as a coefficient of prediction:

$$C_p = 1 - \frac{\Sigma(P - A)^2}{\Sigma(A - M)^2}$$

where C_p = coefficient of prediction

P = predicted flow

A = actual flow

M = mean of actual flows

C_p is a general measure of forecast accuracy that may be applied for any forecast model. In the case where the forecast model is a simple linear regression with correlation coefficient ρ, it may easily be shown that $C_p = \rho^2$.

The PDI-streamflow correlations indicate that the PDI functions best as a predictor over two time periods: March predicting July, and March predicting June. Coefficients of prediction for the snowmelt model on the Cedar River were computed for these same time spans, and compared to C_p values for the PDI, as shown in Table 6.

Table 6 indicates that the snowmelt model is more accurate than the PDI as a springtime predictor of early-summer flows. As was shown in Tables 2-5,

Table 6. Accuracy of March 31 Streamflow Predictions Expressed as Coefficients of Prediction.

	PDI			Snowmelt Model
Month of Predicted Flow	Sta. 1*	Sta. 2	Sta. 3	Cedar River
June	0.40	0.29	0.38	0.55
July	0.38	0.30	0.42	0.69

*See Table 1

summer streamflows also have high lag one autocorrelations. Therefore, one would expect a combined streamflow and snowmelt model to provide more accurate forecasts of summer streamflows than a prediction method utilizing the PDI. Lettenmaier (1981) has applied a combined streamflow and snowmelt model to the Cedar River. There is no apparent justification for replacing such a forecasting model with a quantitative prediction method based on the PDI.

The drought index is designed to apply to a large geographic area rather than a specific watershed; this is an advantage, in some respects, but a disadvantage in a forecasting application. The index method does not explicitly handle temperature effects such as freezing and melting; in certain circumstances, therefore the index can be misleading. Nevertheless, the correlation study indicates that winter and spring PDI values may provide valuable qualitative information about expected summer conditions. It does not appear that any of the available forecasting methods are useful in predicting September flows, which are determined primarily by September precipitation volumes.

Applicability of Drought Indices to Reservoir Management

The possibility of using the PDI for streamflow prediction in the Cedar/Tolt simulation model described in the following two chapters was considered during the model development stage. The simulation model uses the space rule of Maass, et al. (1962) to apportion releases between the two reservoirs in the system. This rule, discussed more fully in Chapter VI, usually incorporates a long-term forecast of future flows. Preliminary simulation of the system indicated that inflow volumes are so large relative to reservoir storage on the Cedar River that poor long-term flow predictions could cause gross misapportioning of reservoir releases. Therefore, in the Cedar/Tolt model discussed in Chapter III, flows are predicted only one month in the future.

As a result, the required predictions of current and future flows can be made using only lag one correlations. This makes streamflow the more desirable predictor, especially since the flow records have such high seasonal autocorrelation in the critical summer months. Therefore, there is no apparent reason to include the lengthy PDI calculation in the management model, although this could conceivably be done. The PDI was also considered for use as a trigger for the application of conservation measures in the model; again, its potential value does not appear to warrant the effort required.

Summary of Drought Index Investigation

The potential usefulness of the PDI as a predictor of streamflow volumes depends on its accuracy relative to other methods. A correlation analysis comparing the predictive abilities of the PDI to those of the streamflow record itself indicates that the PDI is inferior at a lag of one month, but is better at longer lags such as four months. The PDI's greatest potential is as a spring predictor of summer flows, probably because the index indirectly accounts for relative snowpack accumulation. In this respect, however, the index cannot compete with forecast models based on snowpack accumulation and ablation. Therefore, there is no apparent justification for substituting the PDI for other methods in a drought warning or flow prediction scheme, or for including the lengthy PDI computation in the simulation model of the Cedar/Tolt system.

The remainder of this work contains a presentation of a simulation study of the Cedar/Tolt system which emphasizes management of the system under drought conditions. A key aspect of this analysis is the characterization of system reliability in terms of simulated droughts (water supply deficits).

CHAPTER III

THE CEDAR/TOLT SYSTEM

The simulation modeling effort described in the remainder of this report is designed to enhance understanding of the dynamics of the system, especially its performance under drought conditions, and to estimate the effects of proposed system expansion alternatives. This chapter contains descriptions of the system and the proposals for expansion, as well as background information concerning water use conflicts and instream flow requirements on the Cedar River.

Description of the System

The Cedar and Tolt rivers, which originate in the Western Cascades, provide the municipal and industrial (M & I) water supply for the City of Seattle. The existing system (see Figure 16) includes reservoirs on the Cedar River and the South Fork of the Tolt River. Water is diverted from the Cedar at the town of Landsburg; water from the Tolt is diverted at the reservoir. Two major pipelines convey the diversions to the Seattle Metropolitan area. The watersheds of both rivers are restricted to public access and provide high quality water. This supply is supplemented by limited groundwater development in several towns near Seattle. The entire system currently serves about one million residents; the primary demand is residential rather than industrial.

The Seattle area has a mild marine climate, with persistent cloudiness and orographic precipitation due to ocean air rising over the western slopes

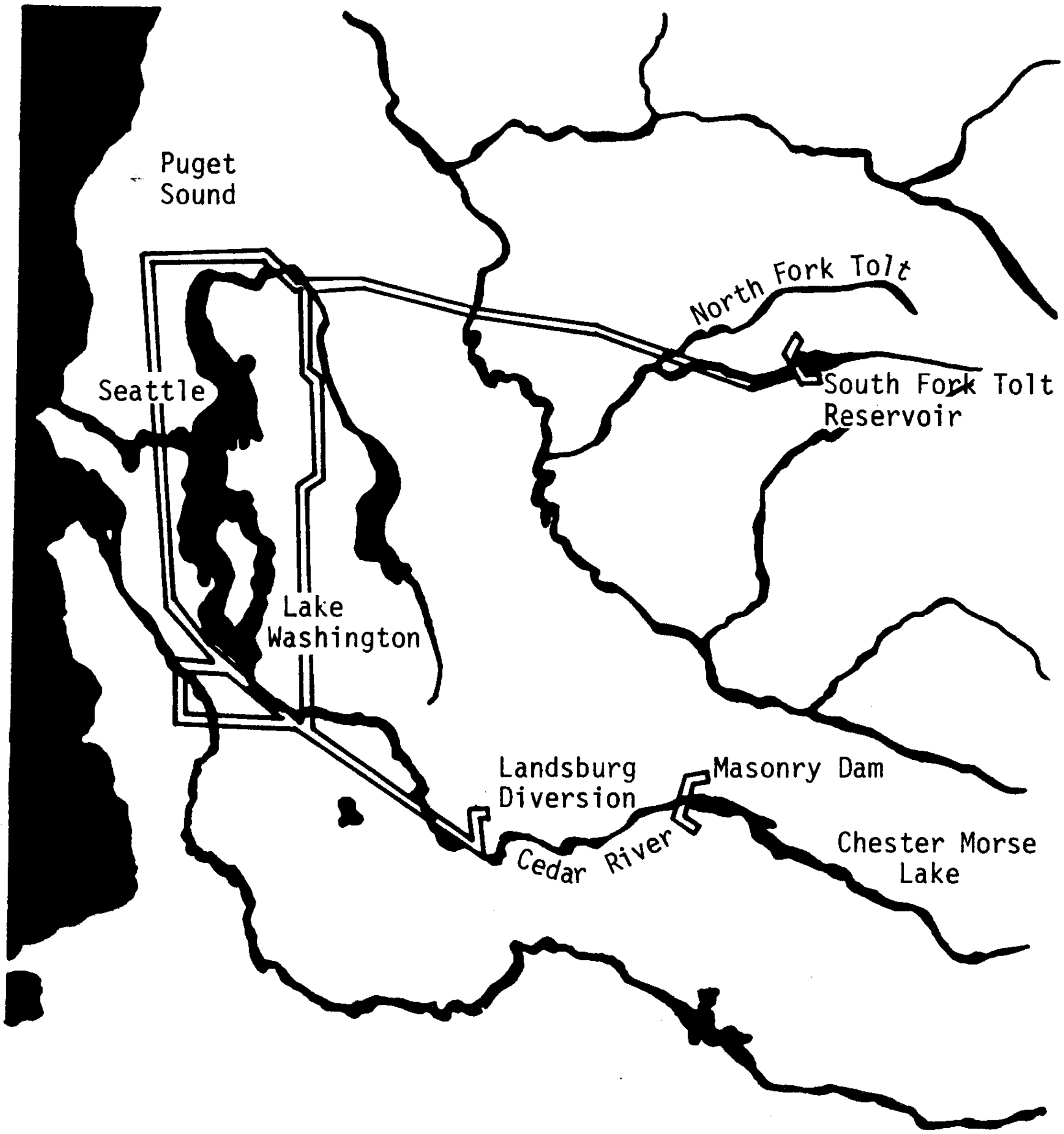


Figure 16. Seattle Area Current Water Supply Facilities (CH2M-Hill, 1974).

of the Cascades. Annual precipitation varies with altitude, averaging 100" to 200" in the mountains and 35" to 50" in the lowlands (CH2M-Hill, 1974). Snowfall may occur from October through June, with accumulations of 300" to 500" in the mountains (Garrow, 1976). The region has well-defined wet and dry seasons in the winter and summer. Streamflows are usually highest from December through February, with extreme floods usually occurring in December and January; winter flows are highly temperature dependent. High flows occur also in April and May when the snow melts, although flooding from spring snowmelt is rare. The lowest flows occur in July through September.

The Cedar River is 50 miles long and drains an area of 188 square miles. The river runs through Chester Morse Reservoir, originally a natural lake, located about 40 miles southeast of Seattle. The drainage area at the reservoir outlet is 81 square miles. The Cedar originally was tributary to the Black River; when the locks connecting Lakes Union and Washington to Puget Sound were built in 1917, the Cedar was diverted to flow into Lake Washington.

In 1901 the City of Seattle began diverting water from the Cedar at Landsburg for M & I supply. In 1904 a wooden crib dam was built at the outlet of Cedar Lake (now Chester Morse Reservoir), raising the lake level and providing additional head for hydropower generation (Miller, 1976). A decade later, a concrete masonry dam was built at a rock-walled point about 7,000 feet downstream from the crib dam (Mackin and Hoover, 1941). When this dam was put to use, severe seepage problems occurred, creating a morainal aquifer in the area and preventing the reservoir from being filled to its intended capacity of 154,800 acre-feet. The active reservoir storage under present operation is small compared to its average annual inflow of 275,000 acre-feet, and can provide only within-year storage.

In 1963, the Seattle Water Department (SWD) built an earthfill dam on the

South Fork of the Tolt River, creating a 57,000 acre-foot capacity reservoir. The South Fork at the dam site drains an area of 19 square miles. A pipeline starting at a regulating basin five miles downstream from the dam carries water from the Tolt to the Seattle distribution system. The Tolt reservoir water is turbid under conditions of high runoff, and is therefore less desirable than Cedar reservoir water (CH2M-Hill, 1974). The Cedar River provides approximately 70 percent of the city's annual water supply. In Figure 17, the relative volumes of storage in the Cedar and South Fork Tolt reservoirs and the mean annual inflows to the reservoirs are compared.

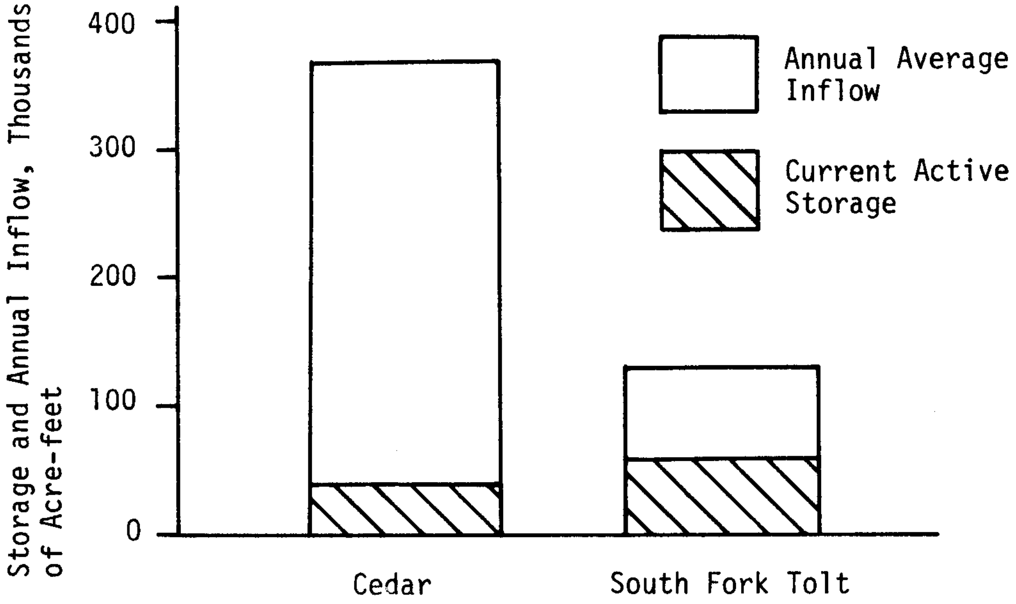


Figure 17. Active Storage and Annual Inflow, Cedar and South Fork Tolt River Reservoirs

The Cedar Moraine Aquifer

The Cedar River system offers a unique management challenge because it includes an underground reservoir filled by seepage from the Masonry Pool and emptying into both the Cedar and Snoqualmie Rivers. This underground reservoir was created unintentionally by the builders of the poorly designed Masonry Dam. A large portion of the storage area behind the dam is lined with open-textured gravels through which a sizeable volume of water began seeping following construction of the dam, forming an aquifer. Seepage loss still occurs whenever water is stored in the pool between the concrete dam and the crib dam upstream. As a result, the Masonry Dam cannot be used effectively to impound the volume of water that it was designed to hold. Most of the water stored in the aquifer later flows back into the Cedar River, contributing a significant fraction of the total Cedar River flow; the rest of the water is lost to the Snoqualmie River Basin.

It is important to remember that the first attempts at filling the Masonry Pool did not merely cause the kind of steady seepage that occurs today, but actually initiated a serious reservoir failure and flooding. Mackin and Hoover (1941) have written a detailed description of the Cedar Reservoir failure. When the Masonry Dam was being built, researchers from the University of Washington pointed out that one side of the gorge between the crib dam and the new dam contained open-textured gravels which were part of a glacial moraine filling a large preglacial valley. The builders disregarded this warning and completed the project. In 1914 the pool was filled to a level well below that of the crib dam. Mackin describes the result:

> "The rise of the water level in the pool was accompanied by a great increase in the discharge of springs in the gorge downstream ... At the end of 30 days the water had practically disappeared from the pool, the rate of loss by seepage being estimated at 30,000,000 gallons per day ... In the spring of 1915 the pool was permitted to fill to a level ... eight feet below the level of the spillway in the old crib dam ... and Rattlesnake Lake, a small water body at the base of the north face of the morainal embankment, increased markedly in size ... Moncton, a town of 200 inhabitants situated near the lake, was flooded and destroyed."

After this occurred, test holes were dug in the gravel material, which turned out to be over 300 feet deep in some places. Some sealing work was done, and in 1918 the pool was filled to a level about ten feet above that of the crib dam. Subsequently, as documented by Mackin and Hoover,

> "... a great outburst occurred in the eastern part of the north face of the morainal embankment ... Detritus aggregating between 800,000 and 2,000,000 cu yd was washed out in a period estimated at between 20 minutes and two hours, leaving a great amphitheater-shaped crater in the embankment face. Discharge of water at the time of the initial outburst was estimated at between 3,000 and 20,000 sec-ft. The flood passed northward through the valley of Boxley Creek to the Snoqualmie River, destroying the tracks of the Milwaukee Railroad, the small town of Edgewick, and sawmills ... Wooden structures in the path of the flood were reduced to kindling, and heavy machinery was moved bodily for distances exceeding one-quarter mile."

According to Mackin and Hoover, it appears that the underground reservoir has a seal of till material; the flood was caused by a failure of this seal.

> "Had the till seal given way nearer to the dam it is altogether possible that sapping by the outrushing waters might have cut a new valley from the base of the embankment to the pool, that the crib dam might have been washed out, and that the whole of Cedar Lake might have suddenly evacuated.
>
> In brief, then, it appears that the implications of this interpretation are decidedly unfavorable to the erection of a concrete dam in the Cedar Gorge ... any program of reservoir development must be based upon exceptionally thorough preliminary testing, with all possibilities in mind."

The Masonry Dam still functions as a flood control structure, but cannot impound water to the 1590' elevation as it was originally intended to do. The present spillway notch in the dam is at an elevation of 1555', about 10' above the crib dam. In the decades following the flood, the rate of seepage loss decreased, probably because of natural silting as well as the earlier sealing work. A rise in the water level of the Masonry Pool results in a marked increase in the rate of seepage loss from the pool, followed after several days by an increase in the discharge of nearby springs.

The volumes of seepage and seepage return flow are significant, and the operators of the reservoir system would like to be able to estimate them accurately. Unfortunately, the flows cannot be gaged directly and must be estimated using available gaged flow records and a water budget approach. In 1976 SWD (Chen, 1976) raised Chester Morse Lake and gaged several streams in the area; they found that daily estimates of seepage could vary considerably. It may be possible to seal the pool to stop or reduce seepage, but such a project is not necessarily worthwhile. Model studies (CH2M-Hill, 1974) indicate that reducing seepage up to the level of the present dam spillway (1555') may not increase system yield; the present underground reservoir provides additional storage and is responsible for a time lag in the release of stored water. If the pool could be sealed up to the 1590' level the yield would be increased, but such a plan may not be feasible.

Seepage return flow from the aquifer passes into either the Cedar River (between the dam and Landsburg), Boxley Creek, or Rattlesnake Lake (Corps of Engineers, 1979). The water in Rattlesnake Lake returns to the Cedar unless the lake level is high, in which case it flows into the South Fork of the Snoqualmie via Rattlesnake Ditch. SWD (Chen, 1976) estimates that seepage loss to the South Fork of the Snoqualmie is composed of 27 percent from Rattlesnake Ditch, 48 percent from Upper Boxley Creek, and 25 percent from subsurface leakage. The volume of return seepage from the aquifer in the Cedar River depends upon the volume of water stored in the aquifer as well as the level of Rattlesnake Lake. SWD found that on the average, about 80 percent of the seepage returns to the Cedar system. This supply of return seepage stabilizes the Cedar River volumes during the dry season.

Future Plans for the Cedar/Tolt System

In 1972 the Corps of Engineers was directed to inventory and inspect all dams in the United States and to identify those not meeting current safety standards. The Tolt and Cedar Masonry dams were inspected in 1978. The inspectors (SWD, 1980) did not find the Tolt Dam unsafe, but did recommend that certain structural elements of the dam be inspected in more detail. The primary safety concerns relative to the dam were: (1) lack of an early warning system; (2) the potential for a slide downstream from the dam; and (3) major dam safety improvements. It is likely that the dam will require some structural modifications. The Masonry Dam on the Cedar, on the other hand, was declared unsafe; a larger, gated spillway must be installed. This modification is part of a proposed Corps project intended to increase the total storage capacity of the dam for flood control and lockage flow supply. The proposal involves raising the dam and providing the capacity to utilize the present 36,000 acre-feet of dead storage in Chester Morse Lake for water supply and instream flow maintenance. SWD and Seattle City Light also intend to rebuild the old crib dam, raising its level by five feet and providing an additional 6,850 acre-feet of storage that is not subject to seepage loss.

The proposed rebuilding of the Cedar River dams assuredly will increase the size of the supply available from that system. The city must, however, provide additional expansion of its supply system to meet projected future demands. SWD (1980) has developed a comprehensive plan (COMPLAN) with the goal of making the Seattle water system "reliable for emergency situations and capable of delivering sufficient quantities of water to the main supply lines to meet 7-day peak and peak day demands through the year 2025". SWD currently serves about one million residents and expects to be serving 1.5 million in 2025.

In 1971, SWD and the Municipality of Metropolitan Seattle (METRO) performed a water resource management study (WRMS). This study was coordinated by the River Basin Coordinating Committee (RIBCO) and is referred to as RIBCO-WRMS (CH2M Hill, 1974). The study evaluated a number of potential structural methods of obtaining more water for the city. Several of the more feasible methods are listed here:

1.) Add Cedar River storage by pumping dead storage from Chester Morse Lake or lowering the outlet. Pumping would increase lake surface fluctuation, disturbing lake bed soil and possibly increasing seepage. Turbidity would increase and some fish habitat would be destroyed.

2.) Reduce Masonry Dam seepage by sealing the Masonry Pool. The effect that partial sealing of the pool would have on system yield is uncertain, since the aquifer presently functions as an underground reservoir. Additional feasibility studies must be conducted.

3.) Construct an earthfill dam at the site of the crib dam, which would increase flood storage and active storage without requiring an increase in pool storage.

4.) Construct a diversion structure on the North Fork Tolt River which would include a pipeline from the diversion to the existing regulating basin 10,000 feet away, and a pipeline to Seattle. Rights-of-way and land use permits have already been negotiated.

5.) Withdraw water from Lake Washington, which would insure that fish flow requirements could be met without a reduction in M & I withdrawal. Lake flushing would be increaesd. Water treatment would be required, but might eliminate the need for a closed Cedar River watershed. Lockage and lake level requirements must be considered.

6.) Develop water sources outside of the Cedar/Tolt system including groundwater diversions from the Snoqualmie River, or the North Fork Skykomish River, and interties with the Everett and Tacoma supply systems.

The current plan for expansion includes the addition of Cedar River storage, some groundwater development, and diversion from the North Fork of the Tolt River. The city plans to start designing the Tolt diversion in 1983 (SWD, 1980). Seattle City Light will construct power generation facilities on the Tolt regulating basin and on the North Fork Tolt. The city plans to request a water right permit for about 110 cfs from the North Fork Tolt.

Water Use Conflicts on the Cedar River

A major issue affecting management of the Cedar River system is the conflict between potential uses of the water. (A similar conflict exists in the Tolt River basin, but only the Cedar will be discussed here.) Cedar River water is used in a number of ways:

1.) Water Supply
2.) Power Generation
3.) Fish Production
    a.) Spawning and Rearing Habitats
    b.) Fish Ladder Flow at the Locks
4.) Water Quality
    a.) Dilution and Flushing
    b.) Prevention of Salt Water Intrusion to Lake Washington
5.) Navigation/Transporation
    a.) Lockage Flow
    b.) Prevention of Damage to Floating Bridges
6.) Recreation/Aesthetics

Items 3 through 6 represent instream flow needs. Water used for municipal supply is diverted at Landsburg, reducing the instream flow below that point and, subsequently, the inflow to Lake Washington. Thus municipal use conflicts with instream flow needs.

Several agencies have an interest in maintaining instream flows in the Cedar and Tolt Rivers. The State of Washington Department of Ecology is responsible for setting and implementing minimum streamflow levels. The

Washington Department of Fisheries manages the state's food fisheries; the Cedar River sockeye salmon run is the largest in the 48 conterminous states, and is considered an important resource to protect and enhance. The U.S. Army Corps of Engineers (Corps) is responsible for operating the Hiram M. Chittenden locks and maintaining the level of Lake Washington. The Corps is also responsible for flood control, and thus has an interest in reservoir sizing and operation; this agency also sets upper limits on reservoir releases.

The interests of these agencies often conflict with those of SWD; this has resulted in continuing negotiations regarding the management and use of Cedar River water. The remainder of this chapter is intended to give an overview of the various potential uses for Cedar River water, and the history of the research, legislation, and agency interactions that have affected water use priorities and management policies for the Cedar/Tolt system.

Lake Washington Management Considerations

Instream flow requirements are generally viewed in terms of fisheries and water quality management, but in the Cedar system there is another important consideration. The Cedar River supplies most of the inflow to Lake Washington; Cedar River flows are important in providing for proper operation of both the ship canal locks and the lake itself. The Chittenden Locks were built in 1917 to connect Lakes Union and Washington directly to Puget Sound. As part of this project Lake Washington was lowered eight feet so that it no longer emptied into the Black River. The Cedar River, which had been tributary to the Black River, was diverted so that it drained into Lake Washington and provided sufficient flow through the lake for lock operations. Therefore, Cedar instream flows play a crucial role in Lake Washington management.

A flow of fresh water through the lake also serves to maintain water quality. The greatest potential pollution problem in the lake is directly related to the locks. During each lockage, some salt water enters the lake; the Corps of Engineers (1979) has estimated that during the summer as much as 900 tons of salt may pass into the ship canal during a single lockage. The salt forms a wedge that moves further into the lake during the summer and is pushed back by increased freshwater inflow during the fall. To prevent more serious intrusion, a gravity-fed drain pipe has been installed through which salt water can flow back into the Sound. Even with the drain in use a salt water wedge may reach the Montlake Cut, about five miles east of the locks, by October in a dry year. The operation of the salt water drain and the lock system itself depends on a sufficient flow of Cedar River water through the lake.

When two floating bridges were built across the lake, it became necessary to limit lake level fluctuations, which would cause structural damage to the bridges. Lake level control is also needed to protect the banks of the lake. Federal regulations dictate that the lake level be kept within a narrow range of elevations. The lake is ideally to be kept at a mean elevation of 21 feet above mean lower low tide of Puget Sound, with a permissible variation of one foot above or below the mean (Corps of Engineers, 1979). The lake is kept at a high level in the spring to store water for summer use, and at a low level in the winter to reduce wave damage and allow for maintenance of structures such as docks. During very dry seasons, maintenance of the lake level may be difficult; records from the period 1953 to 1977 show that the lake dropped below the 20-foot level in about 30 percent of the years. The lack of a requirement for full natural flows at Renton aggravated this problem in some of the driest years.

The management of Lake Washington is now given high priority among potential uses of Cedar River water. The Corps of Engineers has the power to request instream flows that will be sufficient for this purpose. However, the present instream flow requirements are more than sufficient from the Corps' viewpoint; the binding flows are those required to preserve the river's function as a major sockeye salmon run.

The Cedar River Salmon Run and Instream Flow Requirements

The Cedar River has not always been a spawning ground for sockeye salmon. After spawning takes place in a river, young sockeye must migrate to a body of fresh water such as a lake where they remain for a one-year period before migrating to salt water (Miller, 1976). It was not until the locks were built and the Cedar diverted into Lake Washington that the necessary fresh-water body was introduced to the system, turning it into a suitable spawning ground.

In 1926, the Puget Sound Power and Light Company dammed the Baker River, blocking a major sockeye salmon run. Since there were only a few sockeye runs in the 48 states, an effort was made to relocate the run. Beginning in 1937, salmon fry were planted for several years in the Cedar and at four other sites. None of the other sites developed significant salmon runs and the Cedar runs were small until 1958, but then began to increase in size. Now the Cedar River run is by far the largest in the 48 conterminous states. Miller (1976) estimated that it provides an annual net economic benefit of $2.3 million or a net capitalized value of $38 million.

Streamflows in the Cedar River have a profound effect on the success of the sockeye salmon run. Each stage in the life cycle occurs at a particular time of year. Therefore, it is important that mean monthly streamflows lie within suitable ranges required for successful spawning; sufficient within suitable ranges required for successful spawning; sufficient water must also be available for egg incubation, rearing, and natural food production (Garrow, 1976).

Insufficient streamflow affects fish production in several ways. Spawner migration upriver is impaired, and predation on adult salmon increases. Low flows result in a lack of suitable spawning area in the river, causing overcrowding; spawners tend to dig up the eggs of earlier spawners, and increased stress on the fish decreases the success of spawning and increases the rate of mortality of eggs and fry. Insufficient flows occurring in one year can affect the size of the salmon run for several years. Low flows also exacerbate water quality problems such as temperature and low dissolved oxygen.

Flood flows also present a problem, disturbing the streambed gravel and increasing the depth and velocity of the flow beyond the limits required for successful spawning. It is generally agreed that flooding poses a more serious threat to the Cedar sockeye run more than do low flows, and that the existing reservoir system is beneficial to the fishery because it impounds flood waters. Miller (1976) states that the reservoir reduces flood peaks by 35 percent. It is estimated that with natural, unregulated streamflow, the size of the Cedar River sockeye run in 1975 would have been about 80,000; the flood reduction provided by the Masonry Dam allowed an actual average run size of 240,000.

Several research studies have attempted to relate streamflow levels to sockeye salmon production. Different western states use various methods of computing desirable instream flows. The Washington Department of Fisheries method (Collings et al., 1972) sets two flow levels for spawning and rearing. For spawning, the crucial factor is the size of the riverbed area over which both water depth and velocity are in the range that the fish prefer.

Preferred depth and velocity ranges for a particular species can be estimated from field research. For any given discharge, the areas with certain flow depths and velocities can be mapped (Miller, 1976). The area over which both factors are within the preferred ranges can be calculated for each of a number of discharges, and an optimal spawning discharge obtained. In the case of rearing flows, the actual biological requirements of the fish are not known; it is assumed that the optimal rearing discharge occurs when the greatest perimeter of the stream is covered by water at the lowest discharge.

The study by Collings, et al. (1972) provided the basis of the original Department of Fisheries (DOF) requests for instream flows. Collings used data on preferred spawning depths and velocities in the Columbia River, and applied the Washington DOF method to compute a peak spawning discharge on the Cedar of 480 cfs at Renton.

The Seattle Water Department contracted with Stober and Graybill (1974) of the University of Washington Fisheries Research Institute (FRI) to make an independent estimate of Cedar River flows required for sockeye salmon spawning. This study found that on the Cedar River, a wider range of preferred depths and velocities actually exists than had been suggested by the Collings study. The peak spawning discharge was computed to be 250 cfs. In the optimal case,

> "Discharge would ... increase gradually and continuously, reaching 250 cfs on 15 October. At this point, the availability of the maximum area suitable for spawning coincides with the peak spawning activity. After 15 October ... the discharge could be maintained at the peak spawning discharge of 250 cfs at Renton (low runoff regime) ... If water should become available after 15 October due to seasonal precipitation, then the maximum discharge regime (increasing to 480 cfs on 30 November) could be resumed through 30 November. In any case, the highest discharge level attained by 30 November must be maintained until the completion of incubation and emergence of sockeye fry from the gravel the following spring."
> (Stober and Graybill, 1974).

Unlike Collings, Stober and Graybill used preferred depth and velocity data obtained in the Cedar itself; they also used a larger number of reaches in their calculation than did Collings. Despite these improvements, the DOF initially rejected the findings of the new study (Garrow, 1976). Current minimum flow requirements advocated by the State of Washington Department of Ecology (DOE) follow the DOF recommendations.

One assumption implicit in the research described above is that required minimum flow levels should be determined by the biological needs of the fish. Minimum flow legislation passed in Washington State mandates the protection of fish. The same legislation, however, also states that minimum flows should be set so as to provide the greatest public benefit. This leads one to question whether placing fish production as the top priority is the best alternative economically. Miller (1976), while at the University of Washington, carried out a study in which he determined the relationship between streamflow levels and fish production and the value of fish production relative to other uses. He used both a model of the system and a model of fish production and mortality and tested various levels of M & I diversion, using the remaining spawning flows to predict salmon harvests.

Miller found that at a diversion of 310 cfs it would become quite difficult to meet the DOE operating curve, but argued that actual fish production would not be harmed. He also found that M & I supply was by far the most valuable water use for the system. It was determined that benefits are maximized when 325 cfs (the maximum diversion obtainable at present) is taken from the system for water supply. In Miller's opinion,

> "The significance of this analysis is that fish production and its related water requirements should not restrain the development of the Cedar River for water supply. If water supply development is restrained by fish requirements, then net benefits derived from the system will not be maximized. This would result in an economic loss to the people of the state, specifically the Seattle Metropolitan Area. These people would pay

> for this loss in the form of higher water rates which would be required to develop more expensive water supply sources.
>
> Designing the Cedar River water supply system to meet the DOE operating curve during drought conditions would be a gross waste of public funds."

Miller's conclusions are based on purely economic grounds; one can argue that fish are to be protected regardless of whether such an action is economically advantageous. Clearly, research projects cannot indicate the single best course of action in the absence of legal precedents and political priorities. Water rights laws and instream flow legislation provide a background for negotiations among the various agencies involved in the dispute over Cedar River flow requirements.

Water Rights and Instream Flow Legislation

In Washington State water rights are established using a system that can be best described as appropriative. Under an appropriative system, the first user of water from a particular stream obtains the right to use that same amount of water in future years. Only water in excess of that amount may be appropriated to other uses. A water user may store an appropriated share for later use, regardless of downstream recapture use of this water cannot be appropriated to another user. Releases (including seepage) that are not intended for downstream use may be appropriated to another user, but are still made at the discretion of the orignal user (Garrow, 1976).

Under this state's appropriative doctrine, owners of land within a watershed are entitled to use the water for beneficial purposes. The City of Seattle began buying land in the Cedar River watershed in the early 1900's, and now owns about 80 percent of the watershed (SWD, 1980). Land exchanges have been made as well, with the U.S. Forest Service trading logged areas within the watershed for city-owned forest property outside of the watershed.

Virtually all of the remaining land in the watershed is owned by the Weyerhaeuser Company and the U.S. Forest Service, and it appears that the city will own the entire watershed by 2000. The city has been responsible to property owners on Lake Washington for providing water for maintenance of the lake level; prior to 1969, however, instream flows were not protected by state law.

Legislation passed in 1969 required registration of all claims to water rights in Washington State. A water user may now have either an application, which is an established right with legal standing, or a claim, which has no legal standing. Seattle City Light presently has a 200 cfs application for the operation of the Cedar Falls hydroelectric plant, and a 500 cfs claim; the City of Seattle has filed a 400 cfs claim. The city has historically diverted flows of about 100 to 200 cfs from the river at Landsburg (Garrow, 1976).

The 1971 Washington State Water Resources Act, RCW 90.54 (Miller, 1976), provided a state plan for water resource management by the Department of Ecology, and supplied a list of ten guidelines for management, two of which are pertinent:

1.) Allocation of waters among potential uses and users shall be based generally on the securing of the maximum net benefits for the people of the state. Maximum net benefits shall constitute total benefits less costs including opportunities lost.

2.) The quality of the natural environment shall be protected and, where possible, enhanced as follows:

> "Perennial rivers and streams of the state shall be retained with base flows necessary to provide for preservation of wildlife, fish, scenic aesthetic and other environmental values, and navigational values. Lakes and ponds shall be retained substantially in their natural condition. Withdrawals of water which would conflict therewith shall be authorized only in those situations where it is clear that overriding considerations of the public interest will be served."

In accordance with the 1971 Water Resources Act, the Washington Department of Fisheries requested the establishment of flow requirements on the Cedar River (Garrow, 1976). SWD pointed out that the specified minimum flow requirements might exceed the full natural inflows available in certain months. It was agreed that in such cases the natural inflow would govern.

SWD had more basic objections to the base flow request, however. SWD argued that minimum flow requirements should be based upon multiple-use concepts. Both economics and water rights dictate that M & I supply should be a high priority water use. The Department of Fisheries argued that base flow requirements should depend upon the biological needs of the salmon, to insure the highest possible level of fish production. Both the 1969 and 1971 Acts require that existing salmon runs be preserved and that water resources be managed in the best interests of the public. This is difficult to interpret when preservation of the existing slamon runs is not the most economical use of the water resource. An optimal flow regime might also enhance fish production, not merely protect it.

The Department of Fisheries based its requests on the Collings, et al. (1972) study, specifying a spawning discharge requirement of 480 cfs. SWD supported the Stober and Graybill (1974) study, which states that in drought years a spawning discharge of 250 cfs is sufficient and that a higher spawning flow level should only be supplied if the water is available. The final decision was to adopt two minimum flow rule curves, one for normal conditions and one for drought (critical) conditions. The Corps of Engineers stated that the use of either curve would insure that enough water would be sent down to Lake Washington for lockage and level maintenance. The Corps suggested, however, that a 480 cfs spawning flow was too large. The Corps plans to modify the Cedar Reservoir to provide additional flood storage space and thus reduce the size of flood peaks. This would lower the mortality rate of salmon eggs, theoretically providing the same level of fish production with a lower number of spawners, and allowing the spawning flow to be less than the suggested 480 cfs. Subsequently, in 1979 the agencies involved agreed upon 370 cfs as the required peak spawning discharge.

There is no specific rule dictating when drought conditions exist and the critical low-flow curve applies. In dry years, the SWD and the Department of Fisheries establish the river flows by negotiation. DOE mediates the negotiation process, but does not have complete regulatory control since the water rights have not been adjudicated. This process has functioned successfully in the past, but there is continued pressure for the final adjudication of water rights on the Cedar River. The Corps of Engineers, for example, could work more easily toward flood control if water was clearly allocated. SWD would probably benefit from an adjudication of rights, but does not want to bear the cost of such a process. The Department of Fisheries does not favor court action, since the agency cannot claim any rights to the water. DOE benefits from its role as a mediator under the present system. Therefore it appears that for the foreseeable future, instream flows on the Cedar will continue to be agreed upon through a negotiation process.

CHAPTER IV

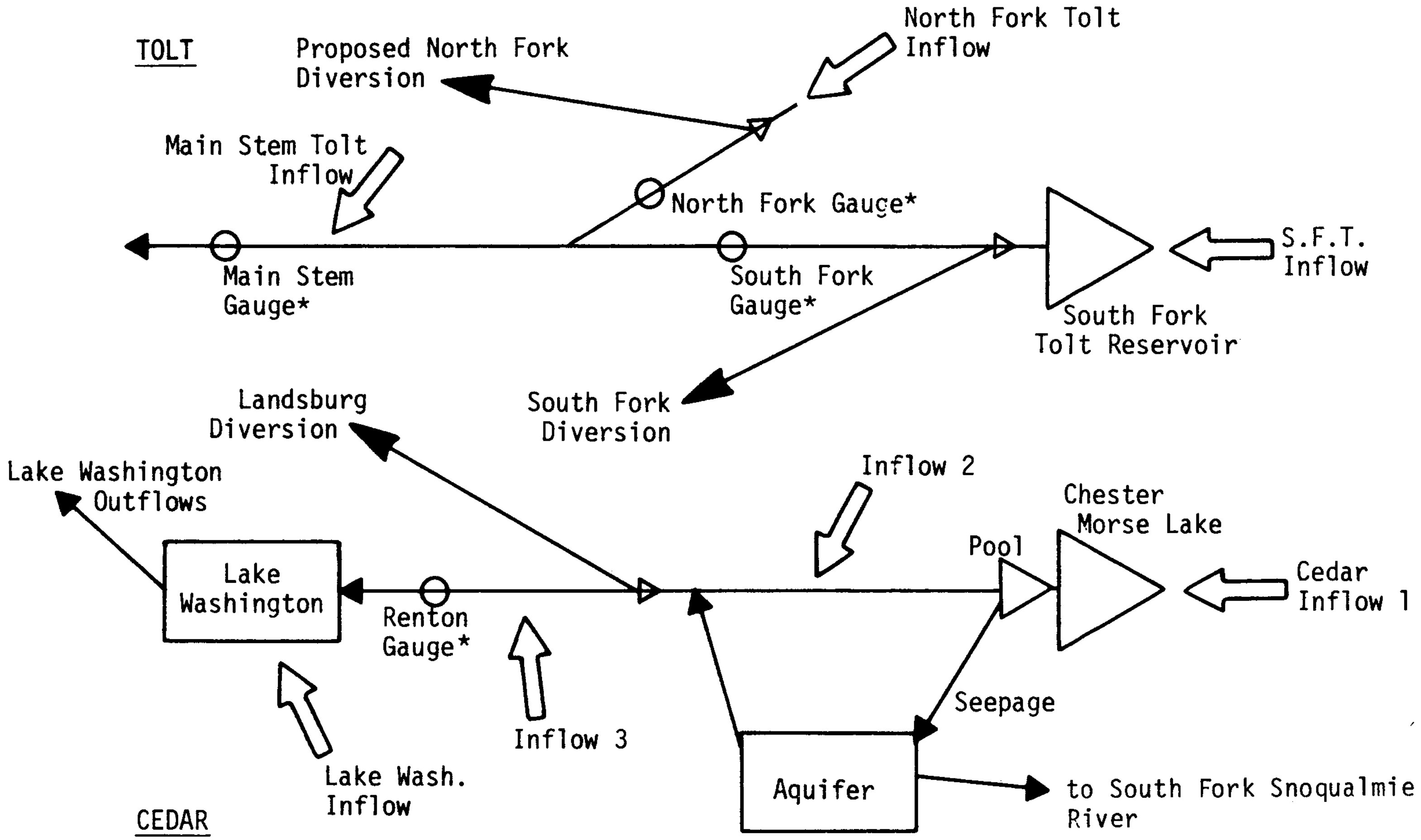
THE CEDAR/TOLT SIMULATION MODEL

The Cedar/Tolt simulation model developed herein is based on a simplified conceptualization of the actual two-reservoir system. Figure 18 shows the simplified system as it is represented in the model. The figure indicates where theoretical point inflows and outflows, river reaches, bodies of stored water, and stream gaging stations are located. Stream gaging stations represent points at which instream flow constraints apply.

Principles of Simulation Modeling and the Cedar/Tolt Model

A simulation model can be used to examine the implications of alternative configurations and operating policies for a water resource system. The optimal configuration or operating policy can conceivably be identified by testing the full range of alternatives by simulation and selecting the one which gives the most desirable results. Such a method will usually require an excessive number of simulation runs, however. In addition, the only alternatives that are tested are those that the modeler chooses to introduce; a simulation model does not generate suggestions of other alternatives.

One solution to this problem is the use of optimization methods such as linear or dynamic programming. An optimization model accepts as input a particular set of goals and constrains that describe a system. Using a solution algorithm, it finds the design or operating policy that best meets the desired goals without violating the constraints. This kind of programming can be used to identify quickly the approximate optimal solution from a vast



*Gauges indicate instream flow constraint points

Figure 18. Schematic Diagram of the Cedar/Tolt System.

range of possible alternatives. On the other hand, such a method generally requires simplification of the system and therefore may give misleading results if used alone. An optimization program can be used to suggest which of the possible alternatives are most worth testing by simulation; the more accurate simulation method can then be applied to a narrower range of alternatives.

When comparing proposed modifications to an existing system, the analyst may need to consider only a small number of alternatives. The system parameters are already known and the design options being considered may have been decided upon by other means such as engineering judgment. When the options are already few in number, simulation modeling becomes an attractive tool for decision making. The implications of each potential modification can be modeled quite accurately, aiding in the selection process. Simulation modeling can also be used to gain an understanding of how a system operates; the values of the state variables (storage, streamflow requirements, and so on) can be observed throughout the sequence. This provides more direct information about a system than a method whose only output is a single set of optimal parameters.

All of the elements of a system that significantly affect the manner in which it functions should be represented in a simulation model of the system. Ideally, the model results should be verified against actual data (such as downstream flows or diversions). Unfortunately, the kind of data on actual operating procedures and streamflows at various locations that are needed for such verification are often unavailable. It is important to model realistic flow prediction methods and operating procedures. Care should be taken not to model operating policies that are more complex than those that would actually be used. If the model is used to derive operating policies, these rules may have to be quite simple.

A model of a multiple purpose reservoir system may simulate economic benefits. The economic value of each potential water use is estimated, and the optimal system configuration or operating policy (that giving the greatest net economic benefit) is chosen. This kind of analysis is not appropriate for the Cedar/Tolt system; agencies set the required instream flow volumes, and these function as constraints on M & I supply, regardless of its economic value. The Cedar/Tolt system is also a source of hydropower supplementing several Seattle City Light plants on the Skagit River and purchases from the Bonneville Power Administration.

In principle, an economic model could be created, given the existing constraints on M & I supply, to compare the costs of system expansion to the costs of expected supply shortfalls. The Seattle Water Department's priority, however, is to have a low-risk water supply system. The cost of water is relatively low in the Northwest, and it is assumed that the rate increases resulting from system expansion would be acceptable to consumers (Chen, 1980). Therefore, the Cedar/Tolt model developed here computes system reliability subject to existing instream flow constraints; the optimal configuration (or operating policy) is that which is most reliable in meeting M & I demands.

Measuring System Reliability

The term 'safe yield' is often used to describe the draft volume (or base volume multiplied by a particular monthly demand pattern) that can be met without failure for a specified (deterministic) inflow sequence when the system is operated in a predetermined manner.

The term is misleading, however; the safe yield may be computed using any inflow sequence (e.g. the historic sequence), each of which will result in a different safe yield. Therefore, it is more meaningful to consider a probability distribution of system yields. A yield obtained by using many synthetic flow sequences is more likely to reflect the effects of a truly limiting drought, but the use of the word safe is still unadvisable. In any case, in such a yield analysis one or two severe droughts occurring in the flow sequence will usually control the result.

A common approach is to use the historic record to define a design drought with a certain return frequency, and to determine the system's firm yield based on this drought. The application of this method as described in the RIBCO report (CH2M Hill, 1974) makes clear many of the problems inherent in such an approach. The flow record available for that study was too short to define 1-in-50-year low flows accurately, although this is a commonly accepted reliability level for water supply systems. The distribution of the flow deficits among the months of the year had to be decided as well. It was assumed that 50-year low flow conditions as estimated for each month should be combined to make a design drought year, although this results in a design condition much more severe than a 50 year return period would suggest.

Regardless of the method used to define the single critical drought period for yield analysis, the actual significance of such a period in terms of reservoir operation and design or water supply system reliability must be questioned. The critical period defines an approximate lower limit of supply, but does not indicate anything about the amount of water that is available during the usual year or even during a different drought. It may be possible to draw much more than the critical yield from the system if occasional shortages can be tolerated. It is unfortunate that decision makers emphasize safe yield; although such an analysis does provide a single number that can be compared among different system designs or operating policies, the assumption that the computed value has a valid physical meaning is misleading.

One alternative to the concept of firm or safe yield is the measurement of system reliability under certain release targets. Constraints on reservoir operation and water withdrawals are incorporated into the simulation model. Any inflow sequence can be subjected to a demand scenario in the model, and the resulting supply shortages tallied. In a system such as the Cedar/Tolt there is usually sufficient water, but shortages of various magnitudes do occur, especially in the dry season. Simulation model results that indicate the overall reliability of the system during a specified inflow sequence would be more useful than a single number expressing the supply available during some specific drought. Therefore, a method has been developed here that measures system reliability in terms of the nature of the water supply shortages (droughts) that occur during the simulated operation of the system.

Three factors are involved in quantifying system reliability: frequency, severity, and duration of supply shortages. The relative importance of these depends on the nature of the system. In the Cedar/Tolt system, shortages occur in the summer and fall and rarely or infrequently in the winter or spring. Reservoir volumes are small relative to inflow volumes so that overyear storage is insignificant. Supply shortage duration does not appear to vary much. The distribution of shortages within the year, and to some extent the shortage duration, could be altered by applying a contingency plan and is therefore not a measure of intrinsic system reliability. Shortage duration is therefore not reported explicitly in these results. The frequency and severity of droughts is expressed by two parameters: the total number of months in the sequence in which a supply shortage occurs, and the cumulative deficit volume for the entire sequence. In addition, the number of months in which instream flow deficits or volume deficits in Lake Washington cannot be avoided is recorded. In practice, the Corps of Engineers can reduce the volume of lockage or salt water drain flow out of the lake, so some modest lake level failures can be tolerated.

The reliability of a water supply system depends directly on the sequence of inflows that it receives. Historic streamflow records have often been used as simulation model input, but there are some problems inherent in this practice. The same sequence of flows cannot be expected to be repeated in the future; the future may see droughts and floods more severe than those of the past, and the time sequence of hydrologic events will vary. A common method of dealing with this problem is generation of synthetic flow sequences that have the same statistical properties as the historic record but that contain a greater variety of potential hydrologic events than does the historic record. A large number of these sequences are run through the same model and a distribution of results obtained; Bogle and O'Sullivan (1979) refer to this as the implicit stochastic method. It is also possible to incorporate probabilities directly into a model, having both input and results in probabilistic form; this can be called an explicit stochastic method.

In a model incorporating the complex details of a system like the Cedar/Tolt, it is appropriate to use deterministic, or uniquely defined, input and output values. If a single, most representative value of system reliability was desired, the implicit stochastic approach would be the ideal one. This idea has not been pursued due to a lack of computer funds. Moreover, this study has the additional goals of testing the concept of characterizing reliability in terms of simulated supply shortages, and observing how system design and operation affect the resulting pattern of shortages. Comparing results that are all based on the same single sequence of inflows allows more insight into the behavior of the system.

Description of the Model

The basic functions of the simulation model can be summarized as follows:

1.) The model accepts as input time series of inflow data at seven locations (see Figure 18).

2.) An algorithm computes monthly instream flow requirements at four locations.

3.) On the Cedar River, seepage, aquifer storage, and seepage return flow are computed based on conditions at the beginning of the month.

4.) Instream requirements are used to set minimum reservoir release targets.

5.) The additional release necessary to meet the specified M & I demand is apportioned between the two reservoirs, provided that sufficient stored water is available.

6.) The resulting river flows, permissible M & I withdrawals, and ending reservoir storage volumes are computed.

7.) Shortages are computed; at the end of the time series these are used to define system reliability.

The algorithm is implemented by means of a computer program, a description of which, along with a simplified flow chart, is given in Appendix B. In this section, the manner in which each of the processes listed above has been handled in the model is discussed in detail.

Instream Flow Requirements

The first process in each month of the simulation is the setting of instream flow requirements. Instream flow requirements are currently in force on the Cedar River at Renton and on the South Fork of the Tolt below the M & I withdrawal point. (It is possible that flow requirements may someday be set at Landsburg and below the Cedar Reservoir, but no such requirements have been modeled.) When the proposed North Fork Tolt diversion is included in the model, instream flow requirements are incorporated for both the North Fork and the Main Stem of the Tolt. The North Fork requirement merely serves to limit the volume of water that can be diverted from that river in any particular month.

Each of the four flow monitoring stations has, for each of the 12 months, two minimum flow requirements, one for normal conditions and one for critical (drought) conditions. In the case of the Cedar River, SWD is not required to use its stored water to supplement natural inflow, if natural inflow is less than the required (normal or critical) flow. In the case of the South Fork Tolt, the appropriate instream flow requirement, whether normal or critical, must be supplied; if natural inflow is insufficient, stored reservoir water must be released to meet the requirement.

Each month it must be decided whether the normal, critical, or natural flow requirement applies at a particular station. The decision process is difficult to model, because in practice the requirements that apply in any given year result from an agreement between several agencies. In a wet year, SWD attempts to supply the Cedar's normal flow requirement at Renton whenever possible. Natural inflows are also known approximately, and the Renton streamflow need not exceed the sum of natural inflows. During droughts, SWD negotiates with State agencies to reduce the flow requirement at Renton to the critical level.

In the model, this process is approximated by monthly decision rules. A consistent method is applied to set the current month's instream flow requirement based on: (1) the previous month's requirement; (2) the previous month's inflow; and (3) the current month's inflow.

The model also requires that the Cedar instream flow target in any month be sufficient to satisfy Lake Washington level requirements. The flow requirement that has been set is used to estimate the end-of-month level. If this level is below that specified by the Corps of Engineers' rule curve for the lake, then the total lake inflow is increased to equal either the full expected outflow from the lake or the full natural inflow to the lake, whichever is less. In addition, if the lake level is expected to fall below the 20-foot elevation, then stored reservoir water must be used to prevent this. (This interpretation of the lake level requirements was supplied by SWD personnel.)

Target Reservoir Releases

After the instream flow requirements are set, they are used to determine preliminary Cedar and Tolt reservoir target releases, taking expected return seepage into account on the Cedar. When both the South Fork and Main Stem requirements apply on the Tolt, the reservoir release must be sufficient to meet the larger requirement. These instream flow targets are given priority over M & I supply as a water use; releases for M & I supply are appropriated assuming that the water needed for instream flow has already been removed from each reservoir.

Based on the remaining volume of available storage, the M & I demand volume, minus any North Fork Diversion draft, is divided between the two reservoirs using the space rule of Maass, et al. (1962) to simulate optimal reservoir management. The space rule compares a prediction of inflow to each reservoir to the space available in each and apportions the releases so that the reservoirs reach maximum drawdown at the same time and are full and spilling at the same time. The inflows to the two reservoirs were predicted in 3-parameter log normal (LN3) space using statistics derived from the inflow data by Lettenmaier and Burges (1980). In some runs, the sensitivity to flow prediction ability was tested by substituting either the actual future inflows or the monthly mean flows for the LN3-space predictions.

The space rule equation involves a term for total predicted inflow for the remainder of the drawdown cycle in the reservoir. As Figure 17 clearly shows, the Cedar reservoir is too small in relation to its inflow volume for this concept to work well. Therefore when the space rule is used to apportion releases in a particular month, flow predictions are only made for the month in question and one month following. Despite this modification, there are still individual months in which poor predictions cause the reservoirs to be drawn down or refilled unevenly. The space rule compensates for this effect during the following month, however; this is one of the positive attributes of such an operating rule.

Cedar Reservoir Storage and Seepage

The monthly target releases for instream flow and M & I supply are added to find the total desired release from each reservoir. Adjustments are necessary if sufficient water is not available in one or both river systems. End-of-the-month storage in the Tolt reservoir is computed as:

Ending Storage = Beginning Storage + Inflow - Release

Storage accounting in the Cedar reservoir is complicated due to the reservoir's unique characteristics. Storage in the lake and the Masonry Pool are accounted for separately; this is necessary because seepage loss varies with pool storage. If the computed water level is above the level of the crib dam, elevation-storage relationships supplied by SWD (which are given in Appendix B) are used to reset the levels of the two reservoir sections so that they are equal, without changing the total volume of reservoir storage.

Masonry Pool seepage volumes are computed using a pool storage-seepage relationship developed by the Corps of Engineers (1979). Seepage from the pool during any month is assumed to depend on pool storage at the end of the previous month. The use of average pool storage during the month would be more accurate, but this would be difficult to estimate for the two-part reservoir. It is the policy of the operators to keep about 30 feet of water in the pool at all times when the lake level is below the crib dam, so the seepage estimates made at such times are good. Errors in seepage estimation are much greater when the water level is above the crib dam. In months when seepage exceeds initial pool storage, it is assumed that if more water is available in the lake, it is transferred to the pool, where seepage continues. Water must currently pass through the pool to be released. (In addition, the present crib dam leaks water.) More important, the policy of the operators to keep 30 feet of water in the pool allows seepage to continue throughout the month. When the City Light plan (a higher crib dam and use of dead storage) is modeled, the simulated pool level is permitted to go to zero in months when dead storage is being used.

Cedar Aquifer Storage and Return Seepage

The volume of water that is estimated to seep out of the Masonry Pool during a month is added to the storage volume in the Cedar Moraine Aquifer. This aquifer is assumed to have a maximum capacity of 46,000 acre-feet (Chen, 1980). A relationship between aquifer storage and return flow has been developed by the Corps of Engineers (1979). The volume of seepage return flow during the current month can be estimated at the beginning of each time step, based on initial aquifer storage, and thus taken into account when reservoir releases are set. Assuming (based on the best available estimates) that 80 percent of the water loss from the aquifer returns to the Cedar River and 20 percent is permanently lost to the Snoqualmie Basin, aquifer storage is then reduced by 1.25 times the estimated return seepage volume.

Withdrawals and Shortages

Once the releases from the two reservoirs and the return seepage flow to the Cedar have been computed, they are added to the natural inflows occurring below the reservoirs to determine total river flow volumes. These may be used in turn to limit M & I withdrawals. If there is not enough water available to meet both the instream flow requirement and the M & I supply demands, the instream flow requirements are met at the expense of M & I supply. M & I withdrawals from the Cedar and the South Fork Tolt (plus any diversion from the North Fork Tolt) are added to find the total volume of water available for M & I use during the month in question. This volume is compared to the M & I demand target, and any supply shortage is recorded.

System Reliability

The simulation algorithm accepts a single base demand as input and multiplies it by a monthly demand pattern to obtain a set of 12 monthly M & I demands. (The base demand is taken to represent effective average demand and is assumed to remain constant throughout the flow sequence.) The results of the simulation are used to quantify system performance in three ways:

1.) System reliability in terms of M & I deficits
2.) System yield (M & I supply)
3.) System reliability in terms of total deficits

The system reliability method involves applying the simulation process to a single time sequence of flows, at one specified level of M & I demand. The following values are recorded:

1.) Number of months with M & I shortage

2.) Cumulative volume of M & I deficits

3.) Maximum and average monthly deficits

4.) Number of months with Lake Washington level violations; minimum lake elevation

5.) Number of months with instream flow deficits

Determination of the safe yield involves simulating the system at a particular M & I demand level until a month is found during which M & I demands cannot be met. At this point the simulation sequence is begun again with a new base monthly demand 100 acre-feet less than the previous one. This entire process is repeated until a demand level is found that can be supplied throughout the entire flow sequence; this base demand volume is termed the safe yield. A more elegant approach would incorporate a search algorithm.

The expanded version of the system reliability algorithm recognizes the need for recording not only M & I deficits, but total system deficits as well. This version of the model records monthly streamflow deficits relative to the computed flow requirements. Lake Washington storage deficits are computed in two ways: relative to the lake's operating rule curve, and relative to the minimum desirable elevation of 20 feet. Instream flow requirements as intrepreted by SWD (Chen, 1980) make the city responsible for using stored water to keep the lake above the 20-foot elevation but not necessarily above the operating rule curve, so lake deficits relative to the two elevation criteria do not always occur in the same pattern. Total deficits are computed using both definitions of Lake Washington deficit. This expanded analysis indicates the trade-offs that can be made between M & I shortages and instream flow shortages without violating the instream flow requirements assumed by the model.

CHAPTER V

RESULTS OF THE SIMULATION STUDY

In this chapter the results of the Cedar/Tolt simulation study are presented and discussed. The model was used to compare several possible modifications to the existing reservoir system and to estimate the effects of system expansion under increasing M & I demands. The sensitivity of these results to operating procedures was tested as well; this analysis included:

1.) Relaxation of instream flow requirements
2.) Reduction of seepage losses and Lake Washington outflows
3.) Alternate flow prediction method
4.) Alternate reservoir release allocation policy

The results were analyzed in terms of the frequency of shortages, and their cumulative volume throughout the historic time series. (Maximum values of monthly deficit were also computed, but did not appear to vary in any significant way.) M & I supply shortages were of primary interest, but there was also some experimentation with the concept of total system deficits (including instream flow shortages and Lake Washington volume deficiencies). Drought patterns (timing, duration) could also be of interest in a study such as this one, but have not been analyzed here; the exact nature of such patterns could be greatly altered by varying the monthly operating policy. In addition, much of the analysis involved intentionally overstressing the system to make relative sensitivities more obvious, so that many of the modeled deficits would not actually be allowed to occur.

Physical System Modifications

The system reliability program was used to estimate the effects of the proposed expansion of the Cedar/Tolt System. SWD proposes to raise the Chester Morse crib dam and modify the structure so that dead storage in the lake becomes active. SWD also plans to build a diversion dam on the North Fork of the Tolt River. The simulation study compared three system configurations:

1.) The present configuration

2.) The City Light Plan

    a.) Increase height of crib dam by five feet

    b.) Convert 36,000 acre-feet of dead storage in Chester Morse Lake to active storage

3.) The City Light Plan with North Fork Tolt Diversion Dam

    a.) Modify the Cedar Reservoir as in (2) above

    b.) Construct a dam on the North Fork of the Tolt River to divert water for M & I supply, at a maximum rate of 18,000 acre-feet/mo.

The simulation was initially carried out using approximate M & I base demands as estimated and projected by SWD: 12,500 acre-feet/month at present, 17,500 acre-feet/month in 2025. The results in Table 7 are presented in terms of both the number of months (out of 564) in which M & I supply failures occur and the cumulative volume of M & I deficits. The number of months in which the instream water requirements and those of Lake Washington are not met is also of interest. It appears that the modeled instream flow regulations function satisfactorily in preventing Cedar River instream flow deficits and Lake Washington level violations, but cannot insure zero violations, particularly when the system is being highly stressed and storage in the Cedar reservoir becomes depleted. (In such cases, water for M & I supply may still be available from the Tolt.)

Cedar Reservoir Modifications

The results in Table 7 indicate that the present system can supply present demands with a low rate of failure, but cannot be expected to supply the projected year 2000 demand with high reliability. SWD must rebuild the Chester Morse crib dam, and plans to raise it five feet to increase storage and improve system reliability. The model results indicate that raising the crib dam five feet without using dead storage improves system performance only slightly; the use of dead storage is the crucial aspect of the City Light plan. The use of dead storage is also crucial for preventing Cedar system instream flow deficits. Another question considered is whether the dam should be raised higher than five feet. The banks of the lake near the dam are sandy and gently sloping; significantly raising the level of the dam could prove to be quite expensive. The model results suggest that the benefits of raising the dam by ten feet rather than five feet would be small and probably would not justify the additional expense.

Demand-Deficit Analysis

A question of importance to supply system managers is how the system will respond to increases in M & I demand. The curves in Figure 19 were generated by repeated simulation of each of the three potential Cedar/Tolt system configurations over a range of M & I base demands. The plots show the variation in cumulative volume of simulated M & I deficits. The safe yield algorithm was used to estimate demands at which zero failures occur.

Figure 19 shows clearly how much additional information can be generated by using a reliability approach rather than a firm yield calculation. By plotting the performance of various system configurations under increasing demands, the modifications required to keep the system's rate of failure below

Table 7. Effects of Physical System Modifications on System Reliability

Demand (AF/Mo.)	System Configuration	M & I Deficits		Cedar River System Requirement Violations (No. of Months)	
		No. of Months	Cumulative Shortage (AF)	Lake Wash. 20' Level	Renton Flow
12,500	Present	1	761	8	17
------	-------------------------	------	------------	---------	------
17,500	Present	41	420,460	9	28
17,500	Raise Crib Dam 5'	39	387,743	9	30
17,500	City Light Plan (C.L.P.)	4	56,143	0	0
17,500	C.L.P. With N.F. Tolt Diversion	2	12,625	2	2
------	-------------------------	------	------------	---------	------
20,000	City Light Plan	20	218,912	2	1
20,000	C.L.P.; Raise Crib Dam 10'	19	203,488	7	0
20,000	C.L.P. With N.F. Tolt Diversion	9	86,038	1	3
------	-------------------------	------	------------	---------	------
22,000	City Light Plan	46	617,587	12	14
22,000	C.L.P. With N.F. Tolt Diversion	24	298,298	9	15

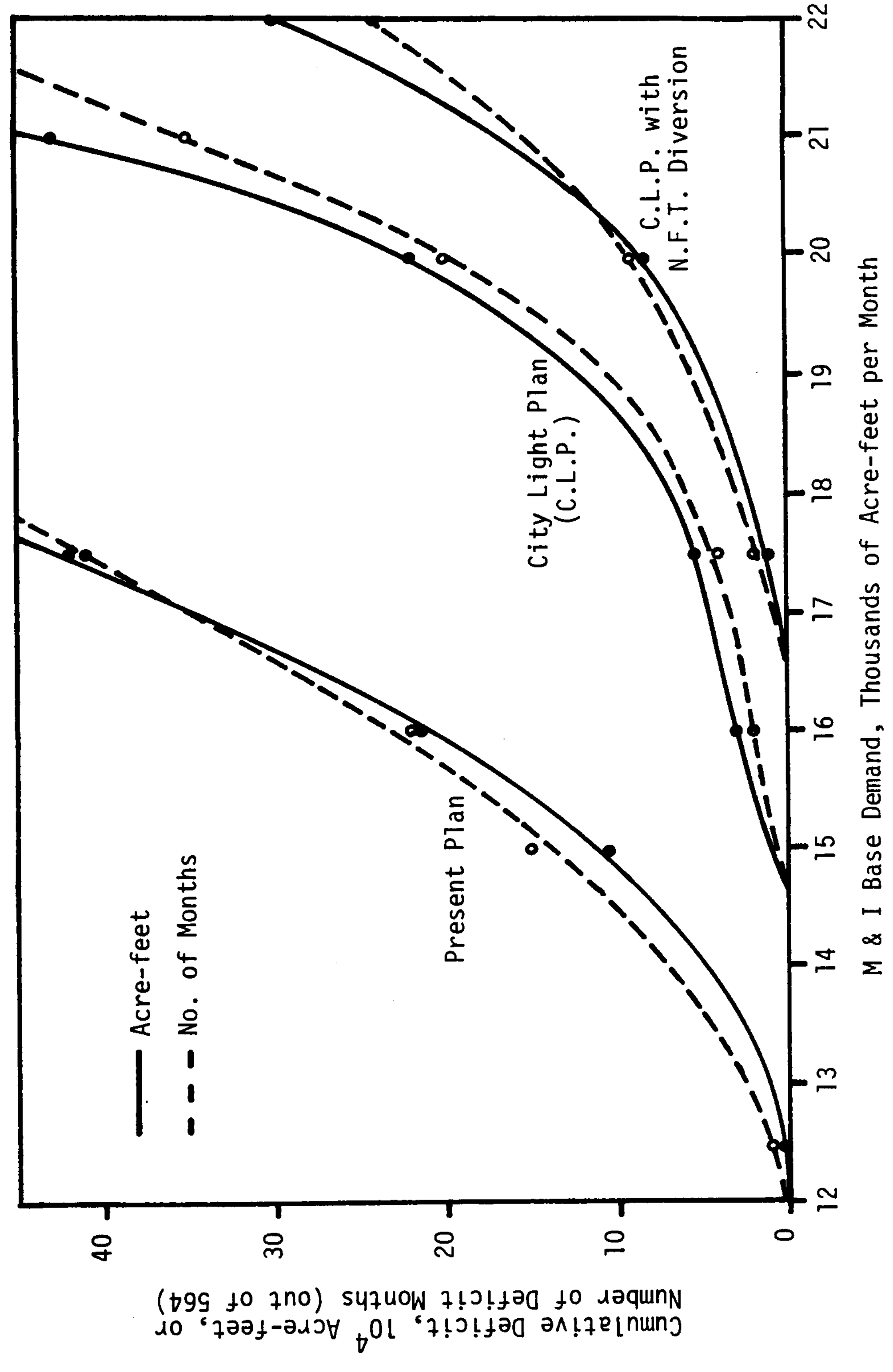


Figure 19. Simulated M & I Deficits Under Varying Demands, Based on Historic Flow Record.

some acceptable maximum can be estimated. Making the most reliable estimate of this failure rate would require an implicit stochastic approach with a large number of synthetic sequences; demand-deficit curves representing various levels of probability could conceivably be generated, or probability distributions of failure rate for each level of demand estimated. The demand-deficit approach could be applied also to an economic analysis, comparing the costs of system expansion to the costs of expected failures in order to determine the demand (year) at which system expansion becomes economically advantageous. At present, however, SWD does not approach the expansion problem in this manner; it considers a low-failure system as its goal, and assumes that the costs of expansion are small enough to be acceptable to the consumers.

The results of this analysis, which are based on the historic record of inflows, indicate that the present system is functioning at a demand level slightly above the 'safe yield' level based on the historic record. The existing system's failure rate can be expected to increase rapidly as demands increase. Therefore, the system must be expanded to supply the projected year 2000 demand of 17,500 acre-feet/month reliably. Implementation of the City Light plan should significantly improve system performance. The addition of a diversion dam on the North Fork of the Tolt River appears to affect system reliability only slightly at demands below 17,000 acre-feet/month, but has a significant effect at greater demand levels. The results of this analysis suggest that the proposed system expansion may not be sufficient to insure a reliable supply of water at demand levels greater than that projected for the year 2025.

Sensitivity to Variations in System Operation

A number of operational procedures were tested to determine the sensitivity of the Cedar/Tolt system to variations in operating policies or requirements. This sensitivity can be expected to differ among the various physical configurations of the system; most of this analysis used the present configuration as a basis. The year 2000 demand projections were placed in the model to generate an unrealistically large number of failures and make the relative effects of various modifications more obvious. The changes in system operation that were tested included: (1) the relaxation of flow requirements; (2) reductions in seepage loss and Lake Washington outflow; (3) variations in the flow prediction method used in allocating reservoir releases; and (4) modifications of the space rule allocation of reservoir levels.

Flow Requirements and Flow Modifications

Table 8 shows some examples of how simulated M & I failures vary with the relaxation of instream flow requirements. The Renton and Lake Washington requirements appear to be of nearly equal importance in limiting the availability of water for M & I supply. Note that the flow requirements on the Tolt's Main Stem and North Fork only apply when the system is expanded to include a diversion dam.

Table 9 shows how system reliability would be increased if certain system flows could be altered. Lockage and saltwater drain flows out of Lake Washington can be reduced under emergency conditions. This may be required in months when there is not enough stored water in the Cedar system to prevent a violation of the 20-foot level requirement in Lake Washington. The elimination of groundwater loss to the Snoqualmie River Basin, on the other hand, is probably not actually feasible; this flow modification was introduced to test sensitivity.

Table 8. Sensitivity to Instream Flow Requirements.

			M & I Deficits	
Demand (AF/mo.)	System Configuration	Requirement Eliminated	No. of Months	Cumulative AF
17,500	Present	None	41	420,460
		Renton	31	294,115
		Lake Washington	33	326,534
		Renton & Lake Washington	22	193,422
20,000	City Light Plan with N.F.T. Diversion	None	9	86,038
		Main Stem Tolt	4	17,172
		All Tolt	0	0

Table 9. Sensitivity to Flow Modifications (Present System Configuration; Demand = 17,500 AF/mo.)

	M & I Deficits	
Modification	No. of Months	Cumulative AF
None	41	420,460
Reduce lockage and saltwater drain flow by 20 percent	35	346,981
Uniformly reduce seepage by 50 percent	30	293,840
Eliminate groundwater loss to Snoqualmie Basin from Cedar Moraine Aquifer	38	375,822

A reduction in seepage flow could be accomplished by lining the Masonry Pool. A 100 percent reduction may even be feasible. Sufficient data are not available for accurate modeling of a partially lined reservoir. As a rough test, seepage flow was uniformly reduced by 50 percent. Preliminary modeling of the Cedar system without the Tolt reaffirmed findings (CH2M-Hill, 1974) that reducing seepage would not significantly increase system reliability because the Cedar aquifer provides useful additional storage. In the case of the combined Cedar/Tolt model, however, a 50 percent reduction in seepage loss from the Masonry Pool allowed greater storage volumes to be maintained in both the Cedar and Tolt reservoirs, decreasing the cumulative M & I deficit from 420,000 to 294,000 AF. This indicates that feasibility studies of seepage reduction may indeed be worthwhile.

Flow Prediction Ability and Release Allocation Policy

In the Cedar/Tolt model, predictions of the current and following month's inflows to the two reservoirs are used in the space rule equation. This rule is intended to assign reservoir releases that will cause the two reservoirs to be drawn down and refilled at comparable rates. The demand-deficit analysis was carried out using lag one flow predictions made in log space (three parameter log normal transformation). To test the sensitivity of these results to flow prediction ability, some simulation runs were made using either perfect flow prediction or prediction of monthly mean flows. Another tested 'poor' prediction: in this run, monthly means were predicted in the Tolt, while for the Cedar, a procedure was developed to give predicted flows with the correct overall mean, but with a reversed trend of high and low flows.

The results of the sensitivity test, which are shown in Table 10, were counterintuitive when expressed in terms of M & I supply alone. By this criterion, prediction of monthly means yields better results than the use of lag one predictions. Examination of detailed model output revealed that while

Table 10. Sensitivity of Results to Method of Flow Prediction

Configuration; Demand	Cumulative Deficit, in Acre-feet (AF) or No. of Months (Mo.)	Perfect Prediction	Lag One	Monthly Means	Poor Prediction
Present Plan; 17,500 AF/Mo.	M & I (AF)	333,901	420,460	333,664	670,249
	Renton Instream (AF)	61,891	64,311	64,222	70,110
	S.F. Tolt Instream (AF)	2,066	2,066	2,066	2,066
	Total Non-Lake (AF)	397,858	486,837	399,952	745,015
	Lake Washington, relative to rule curve (AF)	1,066,709	887,099	1,082,835	1,065,053
	Lake Washington, relative to 20' level (AF)	83,839	52,789	88,951	--
	Total System (L.W. relative to rule curve)	1,464,567	1,373,936	1,482,786	1,810,067
	Total System (L.W. relative to 20' level)	481,696	539,626	488,902	--
City Light Plan with N.F.T. Diversion; 22,000 AF/Mo.	Cumulative M & I (AF)	216,366	298,298		
	M & I (Mo.)	17	24		
	Renton Instream (Mo.)	5	15		
	S.F. Tolt Instream (Mo.)	1	1		
	M.S. Tolt Instream (Mo.)	1	4		
	Lake Wash. 20' Level Violations (Mo.)	5	9		

monthly means were not more accurate than lag one predictions, they generally gave more accurate ratios of Cedar inflow to Tolt inflow, which may have caused the space rule to function more efficiently. In any case, it appears that in terms of M & I supply the results of the demand-deficit analysis based on lag one predictions may be quite conservative.

It was noted that the prediction methods causing fewer M & I failures also caused more Lake Washington level violations. Expansion of the model output format to include the volumes of Lake Washington and instream flow deficits revealed an alternative explanation for the results. During a low-flow period, the monthly means are consistent overpredictions, while the lag one predictions are generally too low. In the Cedar/Tolt system the ratio of inflow to storage is much higher in the Cedar than in the Tolt, and Cedar inflows are significantly greater than Tolt inflows. As a result, the consistent overprediction of inflows to both rivers leads to space rule release allocations that empty the Cedar Reservoir quickly in the spring and early summer, leaving more storage in the Tolt. In later months, all Cedar inflows must be kept instream, where they may still be insufficient to supply the Lake Washington requirement. At the same time, there may still be sufficient storage in the Tolt to fill M & I demands. In contrast, underprediction of flows causes water to be stored in the Cedar; in the summer, this water may all be used for instream demands. Less water is stored in the Tolt, and M & I demands are met less often.

Thus it appears that this experiment, rather than testing the instrinsic worth of flow prediction ability, actually tested the effects of altering the allocation of reservoir releases. Variations in allocation policy do not merely shift portions of an equal total deficit among various water uses, but affect the volume of total deficits. It is tempting to rank flow prediction methods in terms of resulting overall deficits, but it can be seen in Table 10 that these may not follow a clear pattern. Different kinds of deficits have different volumes, affecting the relative size of total deficit figures. An operating policy that stores less water in the Cedar reduces seepage return flows; the Lake Washington requirements in the model compensate for this relative to the 20-foot elevation but not to the lake's rule curve. Thus the relative volume of lake deficits by the two definitions may not correspond. The Cedar/Tolt model was designed to compare M & I supply reliability under a given set of constraining flow requirements; it is less useful for comparing total system deficits.

The model serves to illustrate how reservoir allocation policies can be used to direct water toward different uses. This effect was examined further by altering the space rule's release allocation by various fractions of the total M & I demand, releasing an increasing proportion of water from the Cedar rather than the Tolt. The results of this experiment are illustrated in Figure 20. These plots indicate two things: first, that there is an optimal release allocation policy in terms of M & I supply, and second, that allocation policies may affect the size of the total system deficits in a predictable way.

In terms of system operations, these facts indicate that the operating policy used by the SWD should be of interest to the other agencies concerned with water use priorities on the Cedar River. The Corps of Engineers, for instance, would like to see sufficient water stored in the Cedar Reservoir to insure that Lake Washington can be managed optimally; direct regulation by the Corps of storage levels in the reservoir could serve to benefit Lake Washington management at the expense of M & I supply reliability.

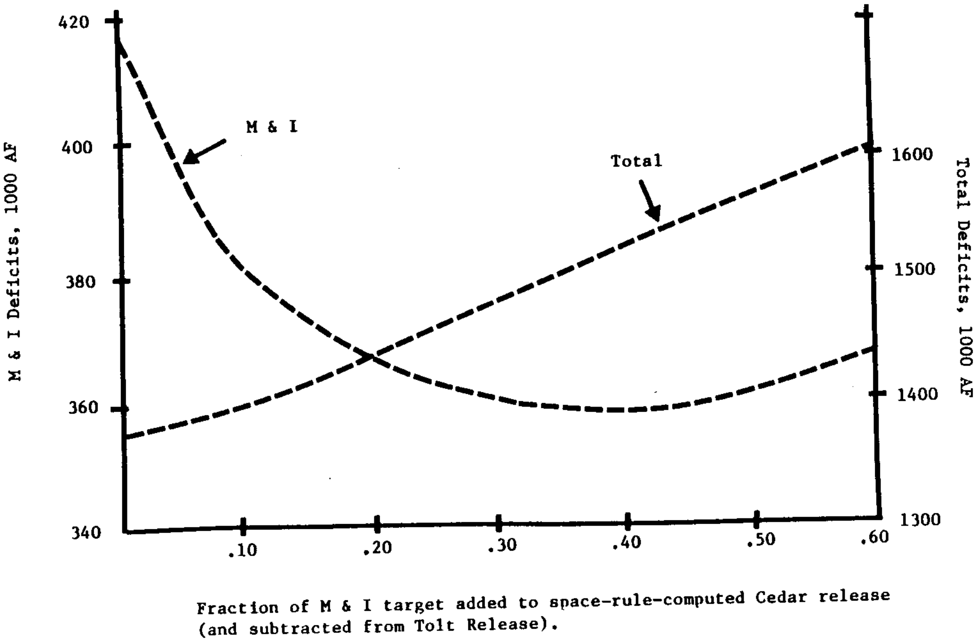


Figure 20. Effect of Modified Reservoir Release Policy on M & I and Total System Deficits

In terms of modeling, these results indicate that the operating policies included in a model of this system have a significant bearing on its results, so that possible physical modifications to the system should be tested using realistic operating policies.

A Comparison of Simulated Water Supply Droughts to Index-Defined Droughts

The results of the Cedar-Tolt simulation model are used here to test informally the accuracy of the Palmer Drought Index (PDI). As was discussed Chapter II, an index is only useful if it accurately indicates drought periods as defined by the relevant effects of drought. In that chapter, the PDI was tested as a predictor or indicator of low streamflow; in this analysis, the index is tested as an indicator of supply shortfalls. The simulation results indicate the supply shortfalls that would occur during the historic sequence if the system configuration-demand scenario, and operating policies remained constant throughout the sequence. This information can be used to define drought years. Simulated droughts in the system are highly seasonal, almost always occurring between July and December. Therefore, the drought severity of each calendar year can be measured in terms of cumulative shortage volume.

In Table 11 the worst drought years occurring between 1931 and 1972 are listed in order of decreasing severity, as measured first by cumulative simulated M & I deficits and second by the minimum value of the PDI occurring during the year. The severity of historic drought years as defined by the two criteria do not correspond well. In addition, when a table of monthly drought indices is compared visually to a table of simulated shortages (not shown here), there is no clear tendency for low index values to precede or to coincide with simulated supply droughts. This suggests that SWD cannot expect a low PDI to predict or indicate accurately periods of water supply shortage.

Summary and Conclusions of the Simulation Study

1.) A detailed simulation model of the Cedar/Tolt water supply system was developed; this model incorporates a method of characterizing system reliability in terms of supply deficits. The model was used to test the reliability of three proposed system configurations under varying levels of M & I demand, based on the historic record of inflows to the system. The senstivity of system reliability to operating procedures was examined as well.

2.) The following conclusions about the Cedar/Tolt system can be drawn from the simulation study:

Table 11. Worst Drought Years, 1931 - 1972

Simulated*		PDI - Defined**	
Year	Cumulative Supply Deficit, 1000 AF	Year	Minimum Index
1941	67	1941	-4.58
1952	34	1944	-4.07
1938	21	1952	-4.02
1934	21	1970	-3.68
1958	21	1967	-3.65
1936	20	1958	-3.28
1963	19	1969	-3.11
1940	11	1939	-2.93
1957	10.5	1938	-2.89
1931	7	1965	-2.88
1965	5.5	1966	-2.73
1943	5	1940	-2.67
1951	1	1935	-2.66

* Present System Configuration, Base Demand = 17,500 AF/mo., Perfect Flow Prediction

**Cascade Mountains West Division

a.) The present system configuration is now being operated at a demand level close to safe yield as conventionally defined. Supply deficits can be expected to increase significantly as demands increase if the system is not expanded. The present system cannot be expected to supply the projected year 2000 demands reliably.

b.) System reliability will be markedly improved by implementation of the City Light Plan. This is primarily due to the effect of utilizing the dead storage in Chester Morse Lake. Raising the Chester Morse crib dam will have a relatively small effect; there is no apparent justification for raising the dam by more than the proposed five feet. The addition of a North Fork Tolt diversion dam to the system will further improve system reliability; however, this project should be viewed as secondary in importance to the City Light Plan.

c.) A significant reduction in seepage loss from the Masonry Pool may improve system reliability, contrary to the results of earlier analyses.

d.) Under the existing set of instream flow regulations, the relationship between M & I shortages and Lake Washington volume deficits depends on the reservoir release allocation policy. The optimal operating policy in terms of M & I supply is different from the policy that minimizes total deficits in the system. The space rule is not an optimal policy in terms of M & I supply, but functions well in terms of total deficits.

3.) The analysis demonstrates the benefits of the demand-deficit approach as compared with conventional yield analysis.

Recommendations for Future Research on the Cedar/Tolt System

1.) Model real-time operations. Simulation involving a shorter time increment such as a week would permit more realistic modeling of system operation and decision-making. The use of shorter time steps would also improve the accuracy of seepage and seepage return estimates.

2.) Perform demand-deficit analyses using synthetic streamflow data. This would indicate the sensitivity of model results to the inflow record, and would lead to better estimates of expected system performance.

3.) Model long-term flow prediction methods. The existing model uses short-term flow predictions in apportioning monthly releases between the two reservoirs. Long-term flow predictions have a much greater potential for use in system management. Snowmelt modeling is one example of a feasible long-term prediction method.

4.) Develop and test conservation plans and apply flow predictions to implementation of conservation measures. Controlled conservation is one means of preventing uncontrolled supply shortfalls. SWD (1980) has already developed emergency conservation plans.

5.) Develop and test alternate instream flow regulations. The modeled regulations are merely an approximation. In addition, it may be possible to design new regulations that function more efficiently.

6.) Develop and test alternate seepage and seepage return models. The existing models contain a significant degree of uncertainty.

7.) Estimate the effects and economic feasibility of seepage reduction through partial or complete lining of the Cedar Masonry Pool. This analysis indicates, contrary to earlier research, that seepage reduction may be an effective means of improving system performance. The physical and economic feasibility of this method should be determined.

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APPENDIX A

SOURCES OF INPUT TO THE CEDAR/TOLT SIMULATION MODEL

The following Cedar River system inflow records were supplied by the U.S. Army Corps of Engineers:

1.) Inflow 1: Inflow to Chester Morse Lake.
2.) Inflow 2: Cedar River inflow between the reservoir and Landsburg.
3.) Inflow 3: Cedar River inflow between Landsburg and Renton.
4.) Local Lake Washington Inflow: All inflow to the lake other than the Cedar, including evaporation.

These flows were not measured directly, but were computed using gaged streamflows in surrounding basins. Computed data were available for the years 1929-1975 only; this is regrettable due to the importance of the 1977 drought. Lake Washington Inflow data were available for the years 1941-1975 only. Monthly means were substituted for the 1929-1941 inflows. This can be considered a source of error, but the generation of additional data does not appear to be justified.

The Corps of Engineers also supplied inflow data for the North Fork, South Fork, and Main Stem of the Tolt River.

The following data are available from the Seattle Water Department:

1.) Lake Washington level rule curve
2.) Reservoir storage limits
3.) Elevation-storage data for Chester Morse Lake and the Masonry Pool
4.) Normal and critical low-flow requirements for the Cedar at Renton, and the Tolt at three locations
5.) Monthly M & I demand pattern (year 2000)
6.) M & I demand projections

7.) Monthly average values of fish ladder flow and gate leakage at the Crittenden Locks, and lockage flow (year 2000)

Table A-1. Examples of SWD System Demands

Month	Projected 2000 M & I Demand, cfs	Projected 2000 Lake Wash. lockage flow, cfs	L. Wash. fish ladder flow and gate leakage, cfs	Lake Wash. operating rule curve, feet
JAN	290	63	47	20.00
FEB	290	75	47	20.00-20.58
MAR	290	77	47	20.58-21.20
APR	290	87	47	21.20-21.80
MAY	341	110	47	21.80
JUN	409	126	47	21.80
JUL	494	138	47	21.80
AUG	477	135	47	21.80-21.34
SEP	341	138	47	21.34-20.90
OCT	290	106	47	20.90-20.44
NOV	290	77	47	20.44-20.00
DEC	290	61	47	20.00

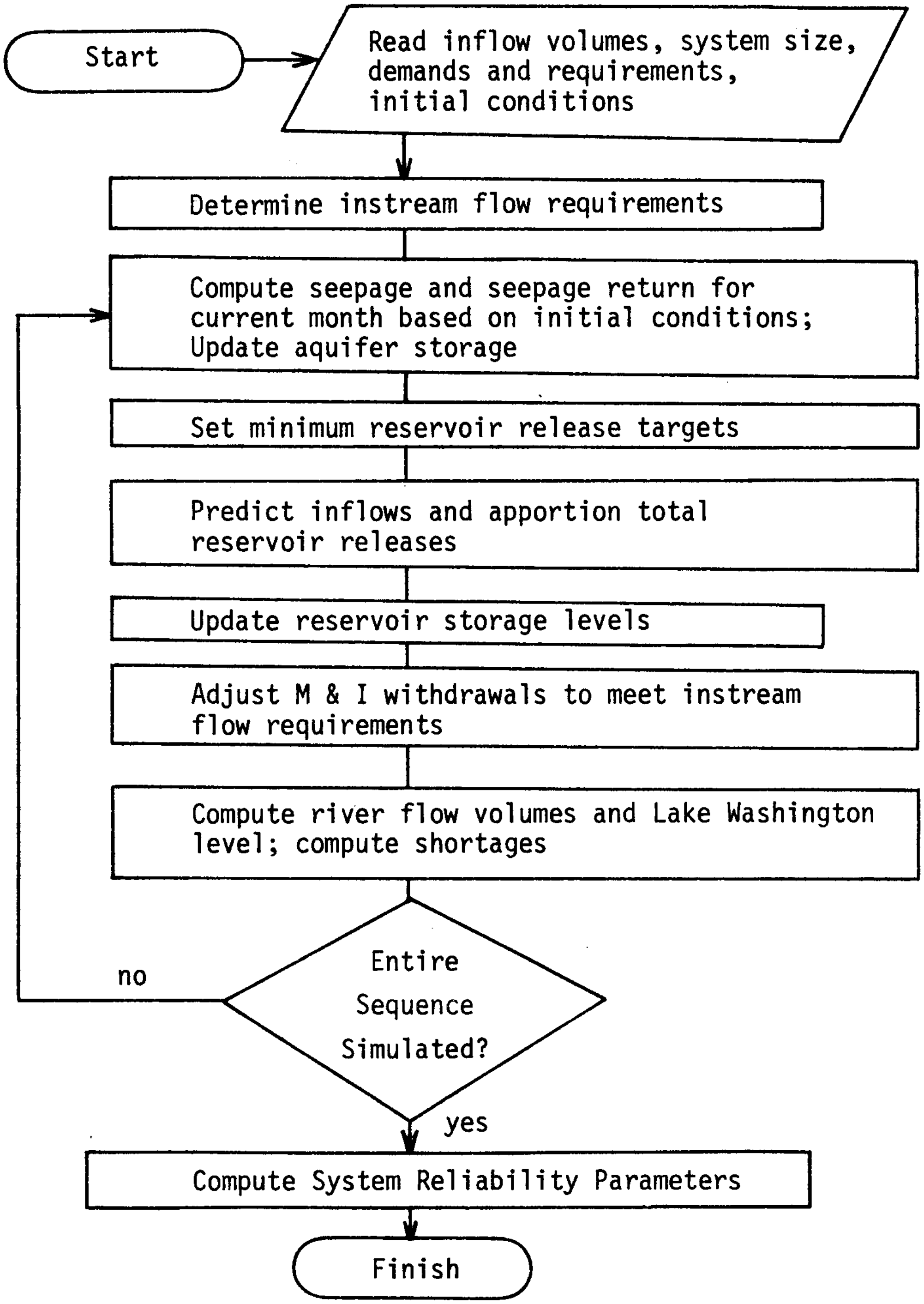

Figure A-1. Flowchart of Cedar/Tolt Simulation Model, System Reliability Computation.

APPENDIX B

SIMULATION PROGRAM DOCUMENTATION

The Cedar/Tolt simulation algorithm is implemented by means of a computer program, utilizing the CDC CYBER 170/750, under the NOS operating system, at the University of Washington Academic Computer Center. The program is designed for use with a CDC FTN5 compiler, which supports 1977 ANSI Standard Fortran.

The program consists of a control file, the Fortran program, and a data file containing monthly parameters and requirements. Streamflow data are stored as a separate file. System configuration parameters, M & I demand level, initial conditions, and applicable instream flow requirements can be varied by altering a small number of lines at the beginning of the program.

The major steps in the simulation algorithm are shown in the flowchart in Figure A-1. Each step is discussed briefly in Chapter VI; this Appendix describes the program in greater detail. A listing of the Program may be obtained from Professor Richard N. Palmer, Department of Civil Engineering, 333-A More Hall, FX-10, University of Washington, Seattle, WA 98195.

At the beginning of the simulation program the system configuration, M & I demand, and inflow sequence length are defined. Indices are used to specify which instream flow requirements are to be in force during the simulation; an index is assigned a value of zero when the requirement that it refers to is to be disregarded. There are four indices, corresponding to the requirements at Renton, on Lake Washington, on the Tolt system, and on the Main Stem of the Tolt. The program then reads the system's initial conditions, monthly flow and storage requirements, average monthly Lake

Washington outflows, and the time series of inflows to the system, as well as the statistics of the flow record that are used to predict flows.

After the input data are read, the instream flow requirements at four nodes are determined. These are computed based on actual flows rather than predicted flows or storage conditions. Each node has two rule curves, for normal and critical conditions. A set of rules developed in conjunction with SWD is used to assign the flow requirement at each location at the normal, critical, or natural flow level, based on the previous month's requirement, the previous month's inflow, and the current month's inflow.

At this point the primary loop of the simulation program begins. The operation of the system is simulated for each monthly time step in the inflow record; the final conditions in any month become the initial condtiions in the following month. The first step that is carried out for each month is the computation of seepage from the Cedar masonry pool, which is related to (initial) storage in the pool as follows:

If S = masonry pool storage, 10^3 AF, then

$$\text{seepage (cfs)} = 57.2*S - 106*S^2 + 120*S^3 - 65.7*S4 + 19.7*S5$$
$$- 3.27*S^6 + 0.284*S^7 - 0.010*S^8 - 0.598$$

This equation was derived from a curve of seepage vs. pool storage. Seepage return flow to the Cedar River is computed based on initial aquifer storage:

Let AQ = storage, 10^4 acre-feet

If $AQ \leq 1.8$, then

$$\text{return (cfs)} = 46.3 - 769*AQ + 3860*AQ^2 - 9000*AQ^3 + 11300*AQ^4$$
$$- 7790*AQ^5 + 2790*AQ^6 - 406*AQ^7$$

If $AQ > 1.8$, then

$$\text{return (cfs)} = 474. - 416*AQ + 264*AQ^2 - 80.0*AQ^3 + 12.2*AQ^4 - 0.727*AQ^5$$

Aquifer storage is increased each month by seepage, and decreaed by 1.25 times the seepage return to the Cedar (see Chapter VI).

Once the instream flow requirements and expected seepage return to the Cedar are known, they are used to compute the volume of water that must be released from each reservoir during the month to meet the flow requirement. In the Cedar, for example, (referring to Figure 18)

Target Release for Instream Use = (Renton Required Flow)
- (Seepage Return Flow) - (Inflow 2) - (Inflow 3)

In addition, if the use of this target flow will result in an unacceptably low Lake Washington level, the instream target release must be increased accordingly.

In the Tolt system, requirements must be met on the North Fork, South Fork, and Main Stem of the river, as shown in Figure 18. Main Stem flow is computed as follows:

Main Stem Flow = (North Fork inflow) - (North Fork Diverstion draft)
+ (South Fork release for instream use) + (Main Stem local inflow).

Therefore, the instream flows on the North and South Forks must be sufficient to insure meeting the Main Stem instream flow requirement.

Once the minimum reservoir release targets have been set, additional releases for M & I supply are apportioned using the space rule of Maass, et al. (1962). The space rule utilizes predicted inflows and current storage volumes to assign optimal reservoir releases. Minimum releases for instream use are subtracted from the predicted inflows before the space rule is applied; thus the operating policy affects only the M & I portion of reservoir releases. Flows are predicted in log space using a lag one Markov model, as is discussed in Chapters VI and VII. After the space-rule-releases are computed, they may have to be reduced or reapportioned due to a lack of water actually available.

Once the final reservoir release volumes for the month are known, ending reservoir storage levels are computed:

Ending Storage = Initial Storage + Inflow - Outflows

The Cedar reservoir is treated as two separate reservoirs. The outflow from the lake is the inflow to the pool. The outflow from the pool includes both the reservoir release and seepage loss. An algorithm simulates management of the reservoir to keep pool storage at the 30-foot level whenever possible. Separate algorithms are required for reservoir drawdown and fill.

Because storages in Cedar Lake and the Masonry Pool are computed separately, the two ending levels may not be equal. In months when the water is above the crib dam, unequal levels are physically impossible. Therefore, a subroutine is used to compute the actual ending reservoir level. This subroutine utilizes the derivatives of the following storage-elevation equations:

If X = pool storage, 10^3 AF, then

$$\text{Pool Elevation (feet)} = 27.8*X - 9.95*X^2 + 2.58*X^3 - 9.37*X^4 + 0.027*X^5 - (8.20*10^{-4})*X^6 + 0.0036.$$

If X = lake storage, 10^3 AF, then

$$\text{Lake Elev. (feet)} = 1.009*X - 0.00669*X^2 + (2.069*10^{-4})*X^3 - (4.63*10^{-6})*X^4 + (4.55*10^{-8})*X^5 - (1.61*10^{-10})*X^6 + 0.0015.$$

The next step in the simulation program is the computation of final M & I withdrawals. If making the desired M & I withdrawals will result in insufficient instream flows or a violation of Lake Washington requirements, the withdrawals must be reduced accordingly. In converting Lake Washington storage volume to elevation, the portion of the lake between the 20' and 22' levels is assumed to have a constant area. In Lake Washington,

$$S = RF + LWI - FSHW - LCK - SWD$$

$$SWD = (14.25 * LLW - 8.67) * CONV$$

where S = change in storage (AF)
RF = instream flow at Renton (AF/mo.)
LWI = local Lake Washington inflow
$FSHW$ = fish ladder flow
LCK = lockage flow
SWD = saltwater drain flow (AF/mo.)
LLW = (initial) Lake Washington level (feet)
$CONV$ = conversion from cfs to AF/mo.

The last step in the program is the computation of the resultant instream flows:

Flow = (upstream reservoir release) - (upstream M & I withdrawal)
+ (upstream local inflow);

and the computation of shortfalls from the target values of M & I supply, instream flows, and Lake Washington storage. When the system has been simulated throughout the entire time sequence of inflows, the deficits are summed to give a measure of the system's reliability, as is described in Chapters VI and VII.